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TROPICAL CYCLONES OF THE NORTH INDIAN OCEAN

by

JAMES C. SADLER and ROSS E. GIDLEY

MARCH 1973

ENVIRONMENTAL PREDICTION RESEARCH FACILITY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93940

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IC (26) (U)
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TROPICAL CYCLONES OF THE NORTH INDIAN OCEAN

by

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Department of Meteorology
University of Hawaii

under

Contract No. N00188-71-M-7003

MARCH 1973

ENVIRONMENTAL PREDICTION RESEARCH FACILITY
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ABSTRACT

Photographs from polar-orbiting meteorological satellites were used in this study to obtain the frequency and tracks of depressions, storms, and hurricanes in the North Indian Ocean from November 1966 through December 1970 plus October 1971.

The distribution of the mean sea-surface temperature, cloudiness, and atmospheric circulation for selected months are discussed in relation to the observed cyclone climatology. Appropriate and pertinent climatic charts of these parameters are presented.

The results from the satellite period are compared with the 70-year (1891-1960) climatology of cyclonic storms from the India Meteorological Department (1964). Plotted cyclone tracks derived from satellite data are presented, as are plotted monthly tracks developed by the India Meteorological Department.

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1. BACKGROUND AND APPROACH

INTRODUCTION

The unique "fingerprints" of tropical cyclones in satellite photographs make it possible to determine their history over data-sparse oceanic regions. Sadler (1964a) utilized early TIROS satellite data to demonstrate a much larger frequency of storms in the eastern North Pacific than had previously been determined from conventional observations. He illustrated that the photographs contain information to stratify the cyclones into depressions, tropical storms, and hurricanes, and that the organization and size of the hurricane cloud canopy is related to maximum winds.

Subsequently, Hubert and Timchalk (1969) used a large sample of satellite photographs and devised a stratification scheme to estimate the maximum winds of tropical cyclones to within a probable accuracy of ±20 kt.

For this study, photographs from polar-orbiting meteorological satellites were used to obtain the frequency and tracks of tropical depressions, storms, and hurricanes in the North Indian Ocean for the period November 1966 through December 1970 plus October 1971.

DATA SOURCES

The principal data source was the daily tropical mercator-projection mosaic of the meteorological satellite photographs from the National Environmental Satellite Service. Supplemental

information from the Indian Daily Weather Report (IDWR) was used when the cyclones were near or over the Indian subcontinent.

CYCLONIC SYSTEM IDENTIFICATION

The systems were identified in two screenings of the photographs. During the first, all systems of estimated storm or hurricane intensity (subjective) were identified and each was tracked backward in time to its place of origin as a depression and then forward to the point of decay. Decay was, in most cases, due to landfall.

The photographs were examined again to identify cloud systems which were associated with depressions that never intensified to tropical storms. This determination was much more difficult and subjective than for storms and hurricanes. Three criteria aided the identification.

(a) The cloud mass must have had "some" organization (usually rounded) suggestive of a cyclonic circulation.

(b) The cloud mass must have either been isolated or, if it was part of a larger cloud field, there must have been distinctive breaks between the cloud mass associated with the cyclonic system and the surrounding clouds.

(c) The cloud mass must have had continuity in the general form of (a) or (b) for at least three days.

Monsoon depressions were excluded from this study. They are difficult to positively identify and track from satellite

photographs. The atmospheric circulation which is favorable for monsoon depressions is also favorable for extensive cloudiness in the northern portion of the Bay of Bengal and the depression cloudiness is most often masked in the larger cloud field. Thus, no data were extracted for July and August. In June and September all of the systems which formed in the Bay of Bengal north of 19N were excluded.

POSITION ESTIMATION

The daily positions of all systems were determined from the satellite photographs. Observations reported in the IDWR were used to verify and adjust the positions of systems along the coast or over the Indian subcontinent.

The error in estimating the center position from satellite photographs varies with system intensity. A study by the Joint Typhoon Warning Center (JTWC) at Guam (1972) compared satellite fixes to the official "best track" positions. The average error for typhoons with discernable eyes was 22 n mi and for tropical storms the average error increased to 54 n mi. The positions of depressions were not compared; however, the average error probably exceeds 150 n mi.

The daily positions were plotted and the track was then smoothed by working back and forth, giving more weight to the days when the circulation was better defined by the cloudiness. Most of the erratic movements were eliminated by this process.

INTENSITY ESTIMATION

The guidelines of Hubert and Timchalk (1969) were followed for estimating the intensity of systems. The storm bulletins in the IDWR were checked for general comparison with the satellite-derived intensities. The intensity definitions used by the India Meteorological Department are:

Tropical depression - winds up to 33 kt

Moderate cyclonic storm - winds 34 to 47 kt

Severe cyclonic storm - winds over 47 kt

No separate nomenclature is used for hurricanes. A severe cyclonic storm with winds of greater than 63 kt is defined in IDWR bulletins as a "severe cyclonic storm with a core of hurricane winds."

The storm intensities from satellite photographs and the IDWR compared quite well for storms in the Bay of Bengal. The comparison was poor, in general, for storms in the Arabian Sea where the IDWR bulletins underestimated the intensities. Storms in November 1966 and May 1970 are used as illustrations.

In early November 1966 a moderate cyclonic storm (IDWR bulletin) crossed southern India and traversed the Arabian Sea (see Figure 10a for track). Satellite views of the storm are shown in Figure 1. The IDWR bulletin decreased the intensity and continued the system as a depression from the 4th through the 7th. The satellite photographs indicate a reintensification of the system to hurricane status by the 6th with winds of near 100 kt. The IDWR increased the system to a moderate

cyclonic storm on the 8th and 9th while the visible eye and canopy size on the satellite photographs would dictate winds of greater than 100 kt.

Photographs of the late May 1970 storm are shown in Figure 2 (see also Figure 6a for track). The IDWR classified the system as a moderate cyclonic storm on the 29th, 30th, and 31st before downgrading to a depression on 1 June. The satellite photographs indicate intensification to a hurricane by the 31st and winds of near 100 kt on the 1st of June before striking the Arabian coast.

The intensities of these two cyclones as published by the India Meteorological Department (1967, 1970) were the same as those contained in the operational bulletins of the IDWR.

TRACKS

The tracks of all systems identified by the screening process previously described are shown in Figures 3 through 11.

NUMBER OF DEPRESSIONS, TROPICAL STORMS, AND HURRICANES

Table 1 lists the number of depressions, tropical storms, and hurricanes by area and month. If a system moved from the Bay of Bengal into the Arabian Sea, it was counted in each area with its appropriate intensity category but was counted only once in the summary for the North Indian Ocean under its most intense category.

Table 1. Number of depressions, tropical storms and hurricanes.

Month	Period	Arabian Sea Dep.	T.S.	Hur.	Bay of Bengal Dep.	T.S.	Hur.	North Indian Ocean Dep.	T.S.	Hur.
January	1967-1970	2	0	0	5	0	0	7	0	0
February	1967-1970	2	0	0	1	0	0	2	0	0
March	1967-1970	0	0	0	2	0	0	2	0	0
April	1967-1970	0	0	0	0	0	0	0	0	0
May	1967-1970	1	0	1	3	2	2	3	2	3
June	1967-1970	2	0	0	0	0	0	2	0	0
September	1967-1970	0	0	0	2	1	0	2	1	0
October	1967-1971	7	0	1	5	5	4	9	5	5
November	1966-1970	3	3	1	3	1	6	5	3	6
December	1966-1970	4	0	0	1	3	2	2	3	2
Total		21	3	3	22	12	14	34	14	16

Approximately 50% (30 of 64) of the cyclonic systems intensified to tropical storms and of these greater than 50% (16 of 30) intensified further to hurricanes.

The number of depressions were about equal in the Bay of Bengal and the Arabian Sea but the probability of intensification was much less in the Arabian Sea.

FREQUENCY OF CYCLONES ATTAINING TROPICAL STORM OR HURRICANE INTENSITY

Table 2 gives the monthly frequency of cyclones attaining tropical storm or hurricane intensity in the Bay of Bengal, Arabian Sea and the North Indian Ocean. If a cyclone was of tropical storm intensity or greater in both the Bay of Bengal and the Arabian Sea, it was counted for both areas but only once for the North Indian Ocean summary.

COMPARISON WITH PRE-SATELLITE CLIMATOLOGY

Frequencies contained in the 70-year climatology by the India Meteorological Department (1964) are also listed in Table 2 for those months which are common for comparative purposes.

The four to five years of satellite data, if representative, indicate that the number of cyclonic storms attaining an intensity of greater than 33 kt is some 75% greater than indicated by pre-satellite data.

One could argue that a comparison of the most intense systems would be more appropriate since these are more sharply defined in the satellite photographs and would perhaps be less

Table 2. Frequency of tropical cyclones attaining tropical storm or hurricane intensity (number per month).

Month	Bay of Bengal		Arabian Sea		North Indian Ocean	
	1891-1960	1967-1970	1891-1960	1967-1970	1891-1960	1967-1970
January	.05	0	.03	0	.06	0
February	.01	0	0	0	.01	0
March	.05	0	0	0	.06	0
April	.26	0	.07	0	.33	0
May	.40	1.0	.18	.25	.58	1.25
June	N/C	0	N/C	0	N/C	
September	N/C	.25	N/C	0	N/C	.25
October (+ 1971)	.76	1.80	.24	.20	.97	2.00
November (+1966)	.80	1.60	.30	.80	1.03	1.80
December (+1966)	.37	1.00	.04	0	0.40	1.00
Jan-May and Oct-Dec	2.70	5.40	.86	1.25	3.44	6.05

N/C not comparable

likely to go undetected in the pre-satellite era. During May, October, and November -- the months of maximum severe storm activity -- there were more than twice as many hurricanes detected from satellite observations (2.95) as compared to severe cyclonic storms of hurricane intensity of the pre-satellite climatology (1.34).

The tracks of cyclonic storms for the period 1891-1960 are reproduced as Figures 13 through 23.

The satellite data show that storms are not as rare in the southwestern Arabian Sea as indicated from previous climatology. During this short period, two tropical storms entered Somaliland and another decayed just off the coast.

The satellite views of the November 1967 storm are shown in Figure 24. The cyclonic system intensified to a tropical storm on the 14th and made landfall on the 15th near 9N (see Figure 10b for track).

Views of the late November 1970 storm which decayed off the coast are shown in Figure 25. This system turned southwestward on the 26th and maintained a well organized circulation into very low latitudes. It was positioned near 2N on the 30th (see Figure 10a for track).

SPEED

The average speed of the cyclones was relatively low in comparison to those in the western Pacific. The average speed during the depression stage was 8.3 kt. It increased slightly to an average of 8.5 kt for tropical storms and hurricanes.

2. SELECTED CLIMATOLOGY

The mean circulation, cloudiness, and sea-surface temperatures are presented (1) as background information for the operational meteorologist and (2) as the framework for viewing the constraints on the formation and life histories of storms.

CIRCULATION

Sadler (1963, 1964b, 1967a, 1967b) has shown that the vortices from which tropical cyclones develop have their origin in troughs oriented approximately east-west. This implies a westerly current equatorward and an easterly current poleward of the trough line.

Low-level troughs exist over portions of the North Indian Ocean region throughout the year (Ramage and Raman, 1972). The intensity, orientation, and latitudinal position, however, are much more favorable for storm development during some seasons than others.

a. Fall. This is the season of maximum storm activity. From mid-September to mid-December, a low-level trough is oriented essentially east-west over the North Indian Ocean. The intra-season position varies from near 20N in late September to near 5N in early December. Figure 26 is the mean October 850 mb circulation. The trough is oriented east-west near 10N with easterly flow across the northern portion of the

Bay of Bengal and Arabian Sea and westerly flow equatorward of the trough -- an ideal low-level circulation pattern for tropical cyclones.

The upper-tropospheric subtropical ridge lies between 15N and 20N in October (Figure 27). It also migrates southward during the fall to a position near 10N in December (Sadler and Harris, 1970; Ramage and Raman, 1972).

b. Spring. This is the second most active storm season. The circulation changes in spring are more rapid and the transition season is shorter than in fall. The storm period is shorter in spring than fall, lasting essentially from mid-April to mid-June.

The mean low-level circulation is also less favorable than in fall. Figure 28 is the mean 850 mb circulation for May. Westerly flow covers the Bay of Bengal and most of the Arabian Sea in the surface and near surface levels, and the trough is weak or absent. The subtropical ridge strengthens with height and by 700 mb (Figure 29) the trough is stronger and more extensive than in the surface levels.

The slight deviation from the mean circulation which produces more favorable conditions for storm development is usually observed as a strengthening of the low-level ridge, producing easterly flow across the central portions of the Bay of Bengal. The key stations for monitoring these changes

are Port Blair and Bangkok where mean westerlies are replaced by an easterly flow.

The mean upper tropospheric circulation in May (Figure 30) is very similar to that of October (Figure 27); however, as in the lower levels, the circulation changes in spring are rapid. The mean position of the subtropical ridge at 200 mb moves from near 9N in April to 25N in June.

c. Summer Mid-June to Mid-September. The mean circulation in summer is not favorable for storm development. The low-level trough is positioned over land and westerlies cover the North Indian Ocean (Figure 31). During the occasions when the trough is observed to be further south than normal and overlies the extreme northern portion of the Bay of Bengal, "monsoon depressions" can form. The depressions move west-northwestward along the trough. Their stay over water is very short and most do not attain tropical storm intensity before making landfall.

The upper tropospheric subtropical ridge is positioned near 30N in July (Figure 32) and August and fairly strong easterly flow covers the northern portion of the Bay of Bengal. The shear in the vertical is not favorable for deep storm formation and maintenance.

d. Winter (Mid-December to Mid-April). During winter the principal trough is the summer monsoon trough of the Southern Hemisphere (Figure 33). The buffer system (Sadler and

Harris, 1970) exists as a trough in the North Indian Ocean eastward from 60E. It lies very near the equator, a position unfavorable for storm formation. Occasionally, or during anomalous seasons, it is positioned between 5N and 10N and can be the seat of depressions. The mean upper tropospheric circulation for January can be seen in Figure 34.

The winter of 1966-1967 was an active tropical cyclone season. The nine depressions which formed between 5N and 10N equaled the combined total for the other three winters. The depressions rarely intensify to tropical storms.

SEA-SURFACE TEMPERATURE

Studies suggest that ocean water temperature should be in excess of 26C for tropical storm development (Palmen, 1956). Figure 35 shows that sea-surface temperatures are seldom a restraint on storm development in the North Indian Ocean. In all areas and seasons experiencing a low-level trough, the sea temperature exceeds 26C.

Other studies (see Brand, 1970) allude to the influence of sea-surface temperature on storm movement and intensity. The late autumn or winter storms may have their intensity and/or direction altered if they move over colder waters of the western Arabian Sea or northern Bay of Bengal, but such an effect could not be tested with this data sample.

CLOUDINESS

The mean cloudiness for January, May, July, and October is depicted in Figures 36 through 39.

There is no obvious relationship bewteen zones of mean maximum cloudiness and areas of maximum frequency of storm development and tracks. The maximum cloud zones, in general, lie in the deep low-level westerly currents equatorward of the trough. Storms develop in the trough and, in general, move poleward. This does not imply that there are no clouds in the vicinity of developing storms, only that storms are transient features and the associated cloudiness is compensated by the enhanced minimum cloud area surrounding the storm.

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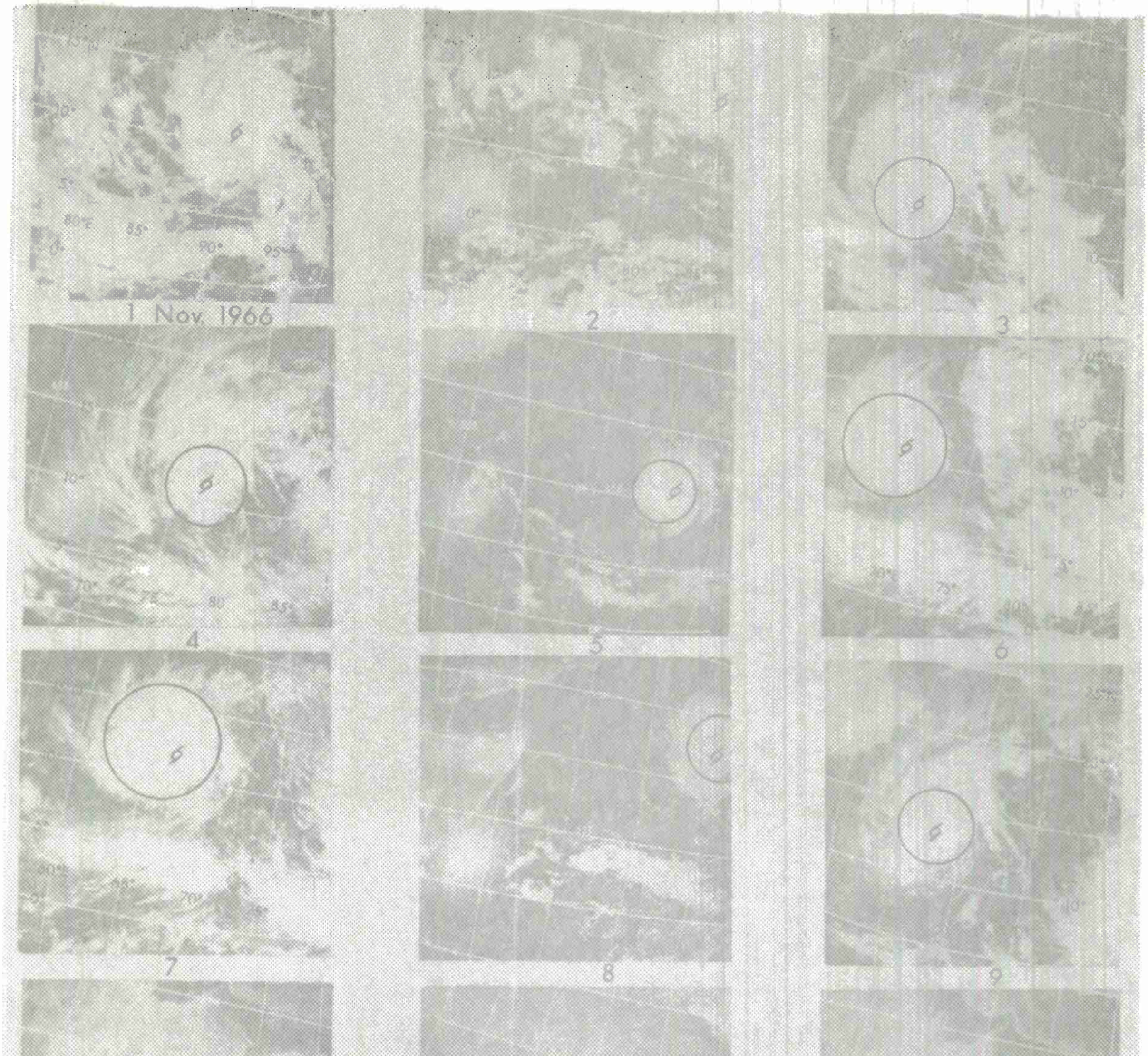


Figure 1. Satellite views of a moderate cyclonic storm in the Bay of Bengal and Arabian Sea (November 1966)

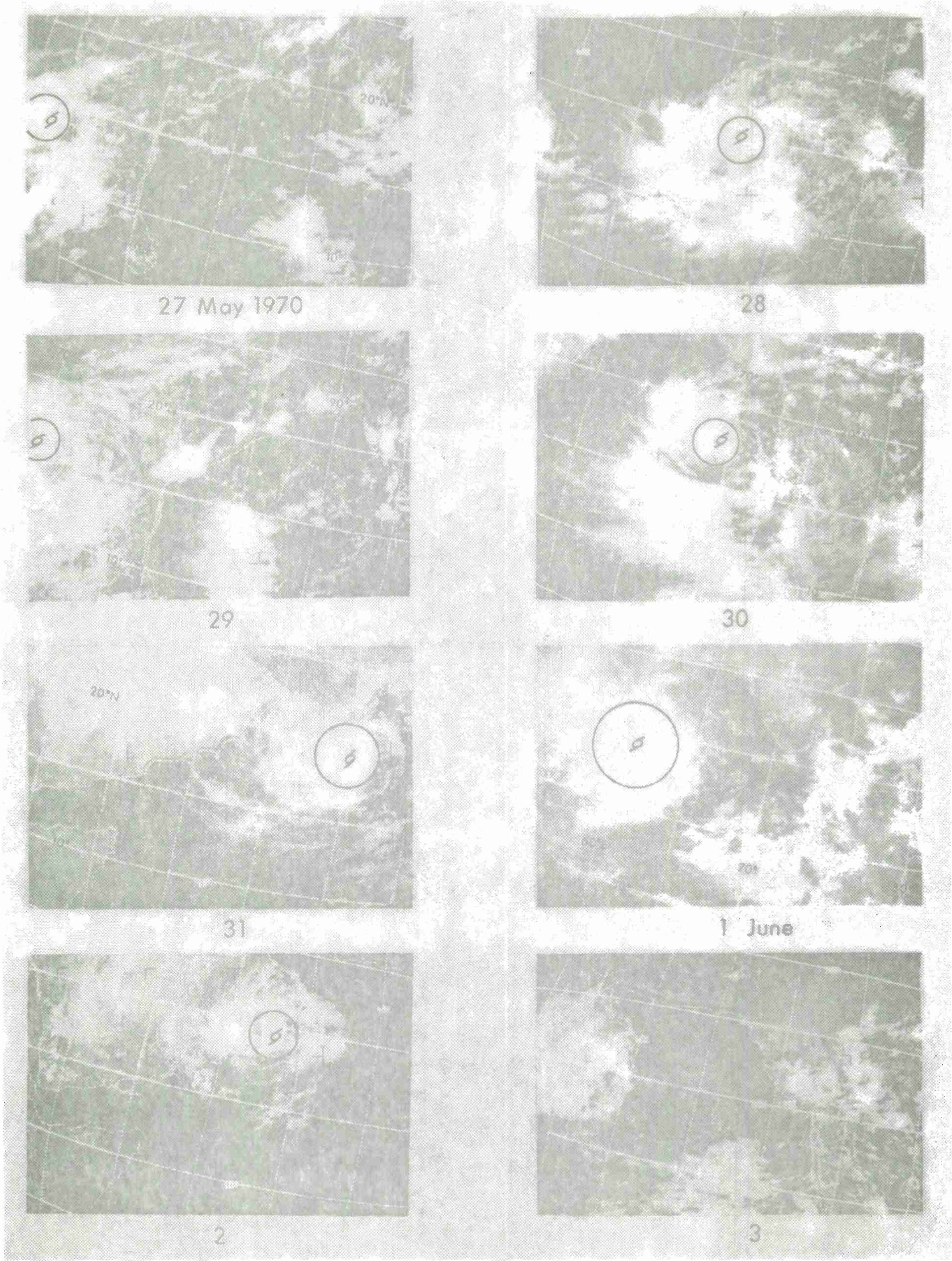


Figure 2. Satellite views of a moderate cyclonic storm in the Arabian Sea (May 1970)

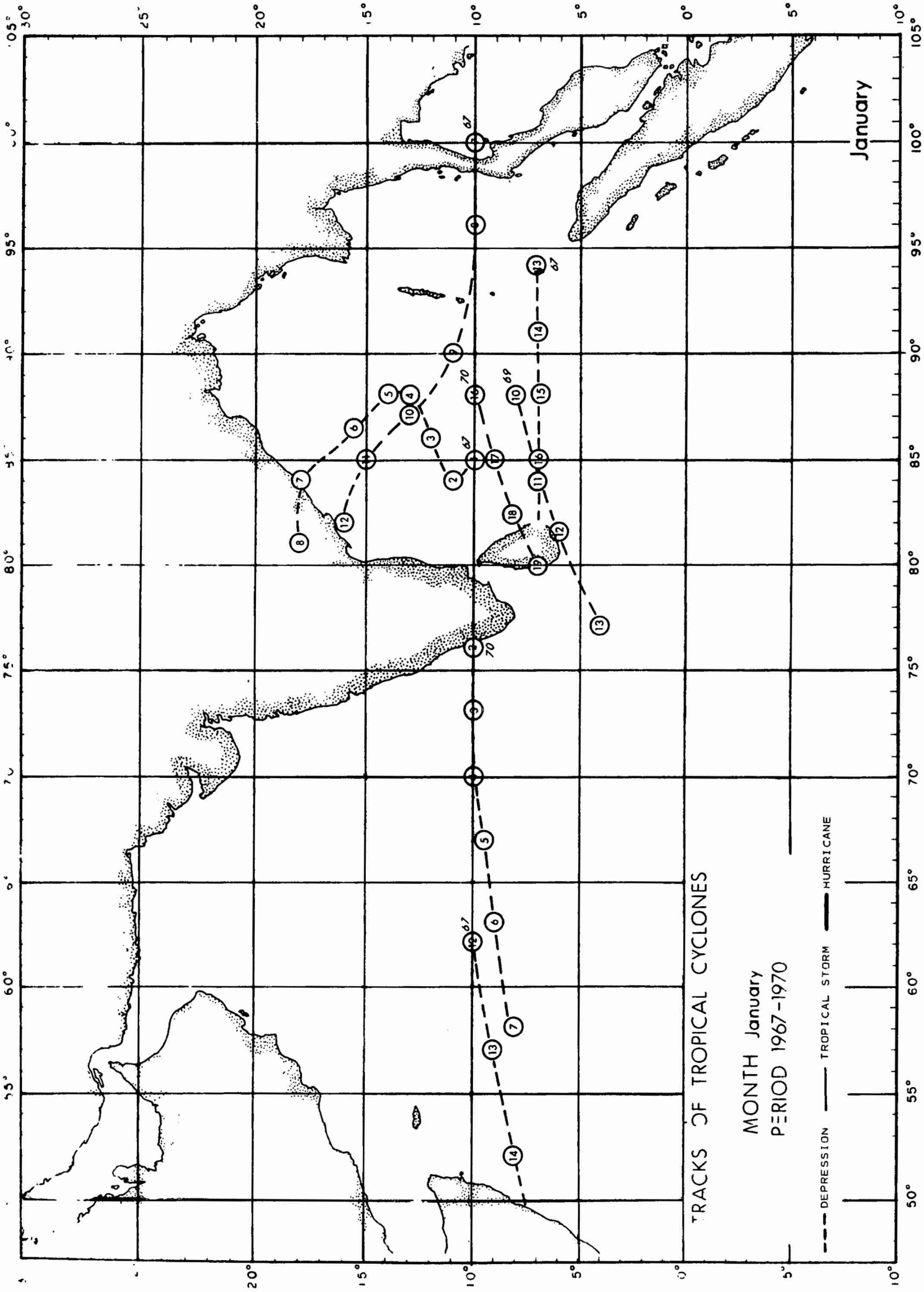

TRACKS OF TROPICAL CYCLONES
MONTH January
PERIOD 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
January

Figure 3

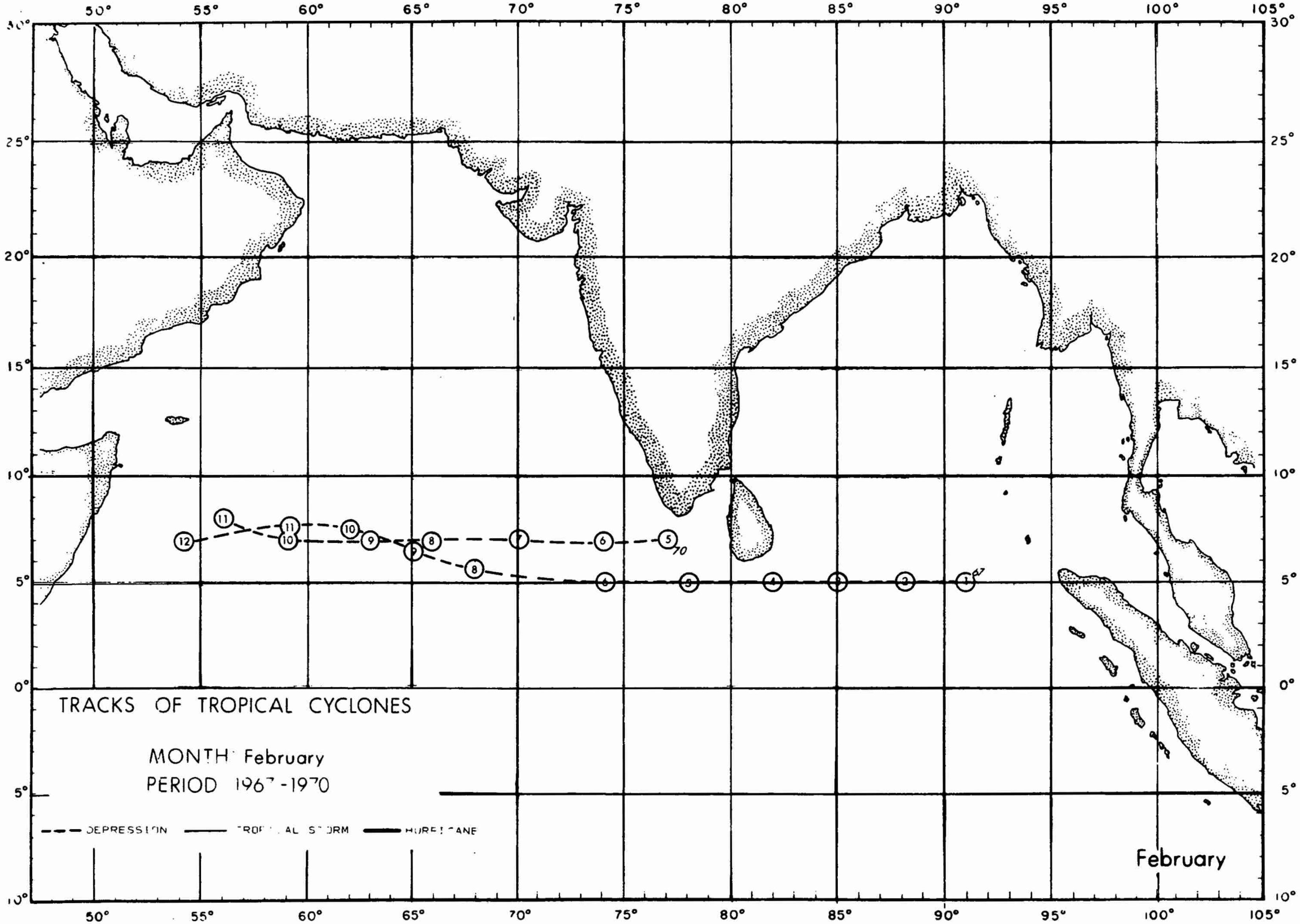

TRACKS OF TROPICAL CYCLONES
MONTH February
PERIOD 1967-1970
February

Figure 4

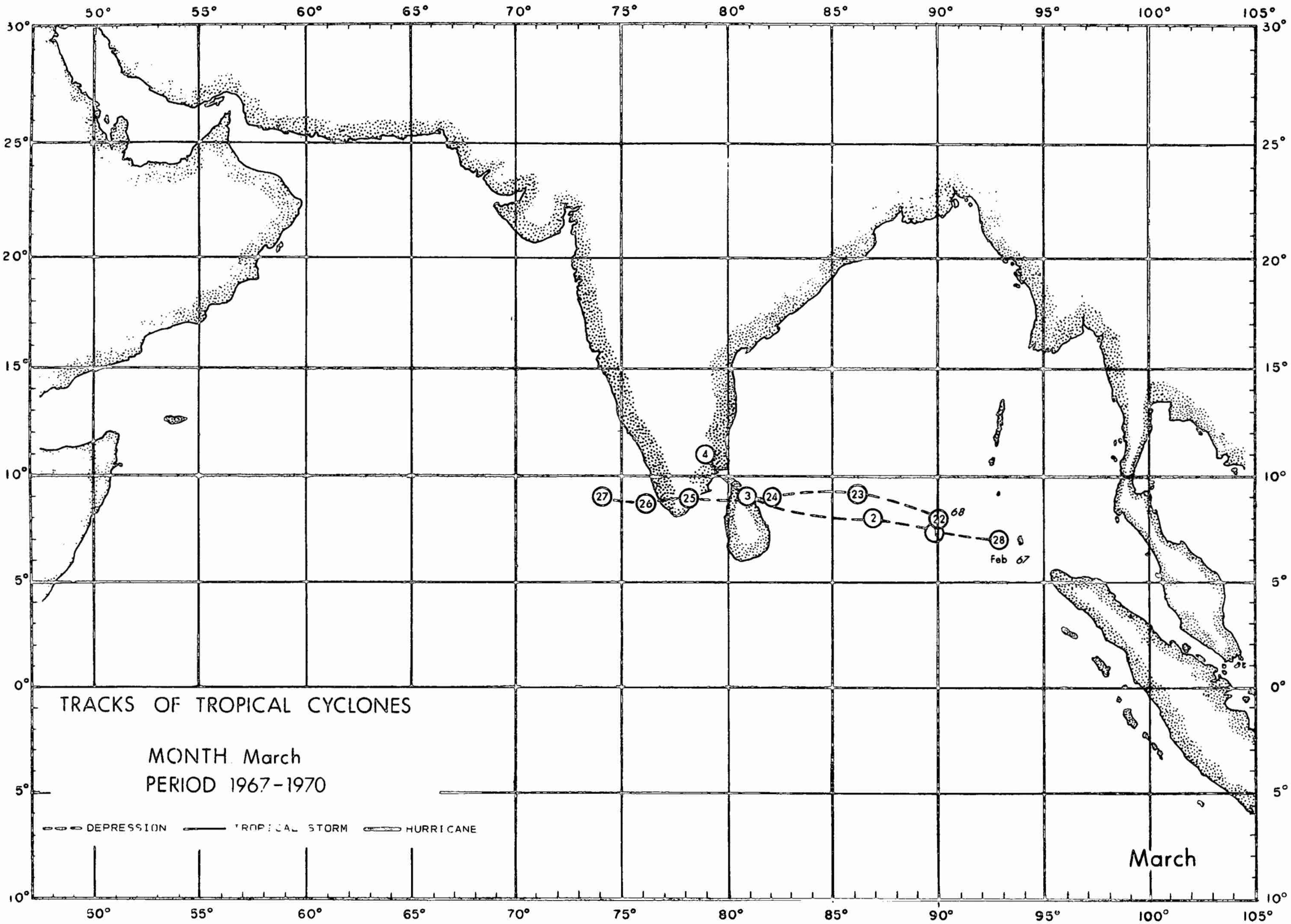

TRACKS OF TROPICAL CYCLONES
MONTH March
PERIOD 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
March
Feb 67
68
27
26
25
4
3
24
23
2
22
28
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
105°
30°
25°
20°
15°
10°
5°
0°

Figure 5

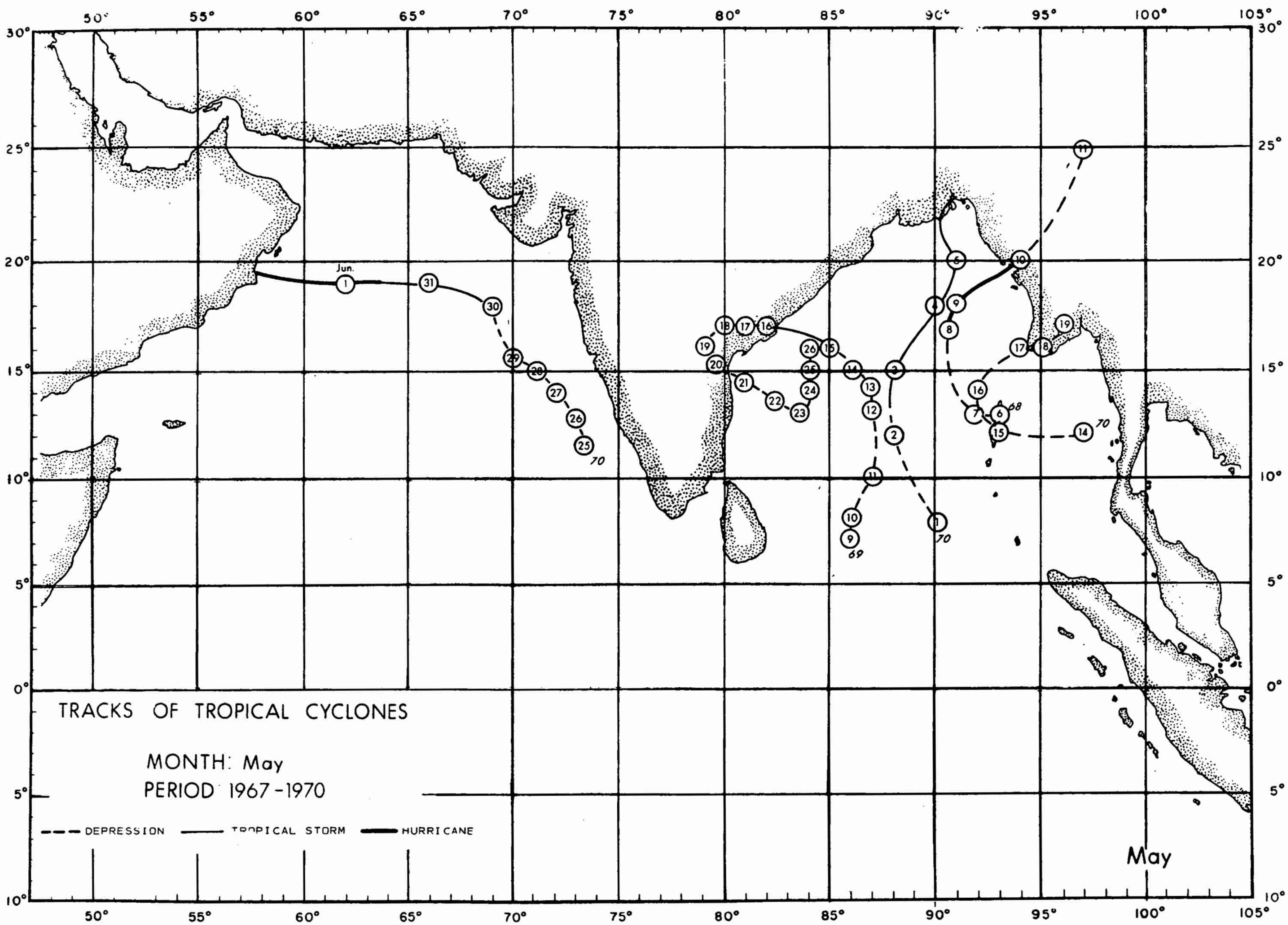

TRACKS OF TROPICAL CYCLONES
MONTH: May
PERIOD 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
May
Jun.

Figure 6a

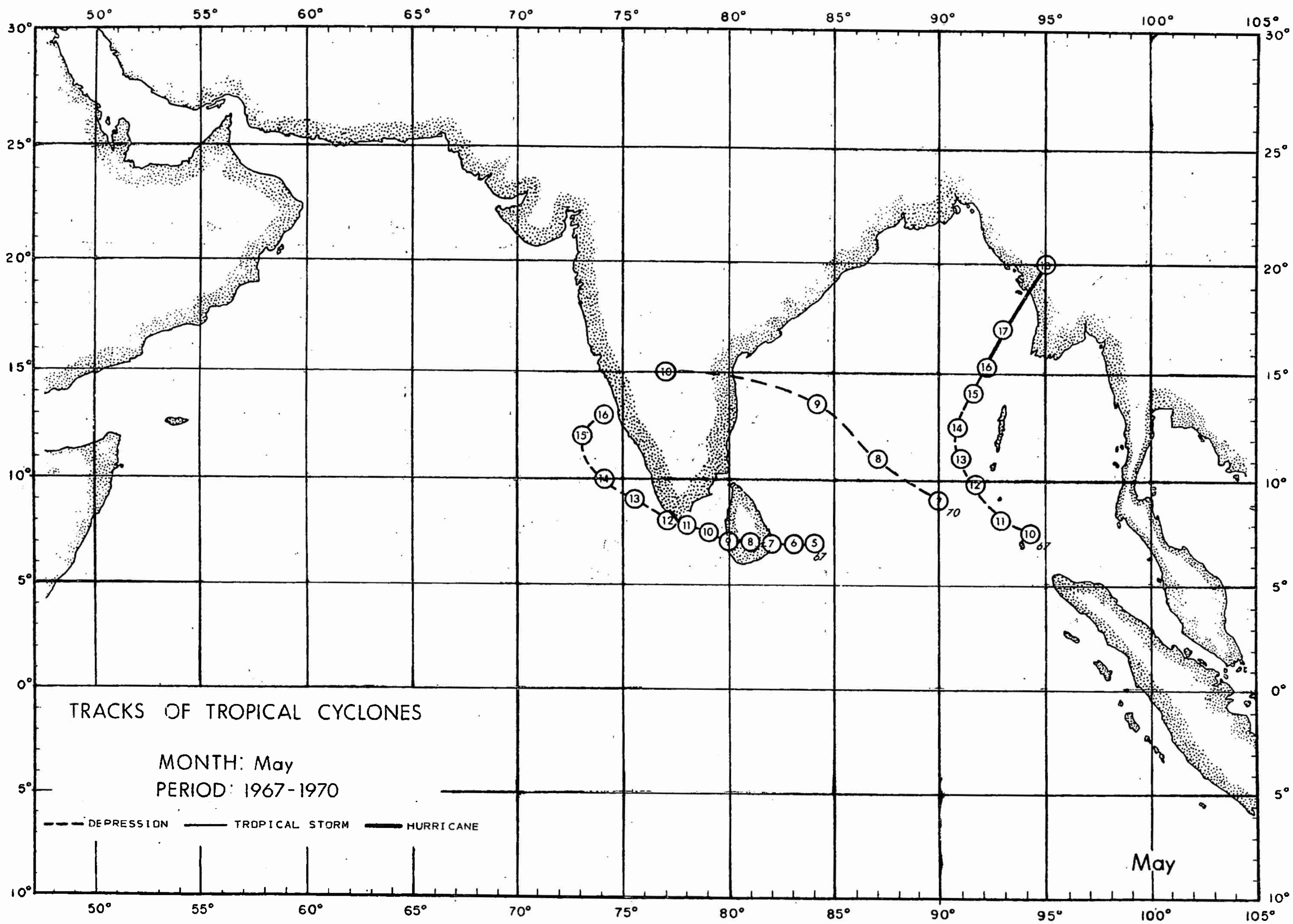

TRACKS OF TROPICAL CYCLONES
MONTH: May
PERIOD: 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
May

Figure 6b

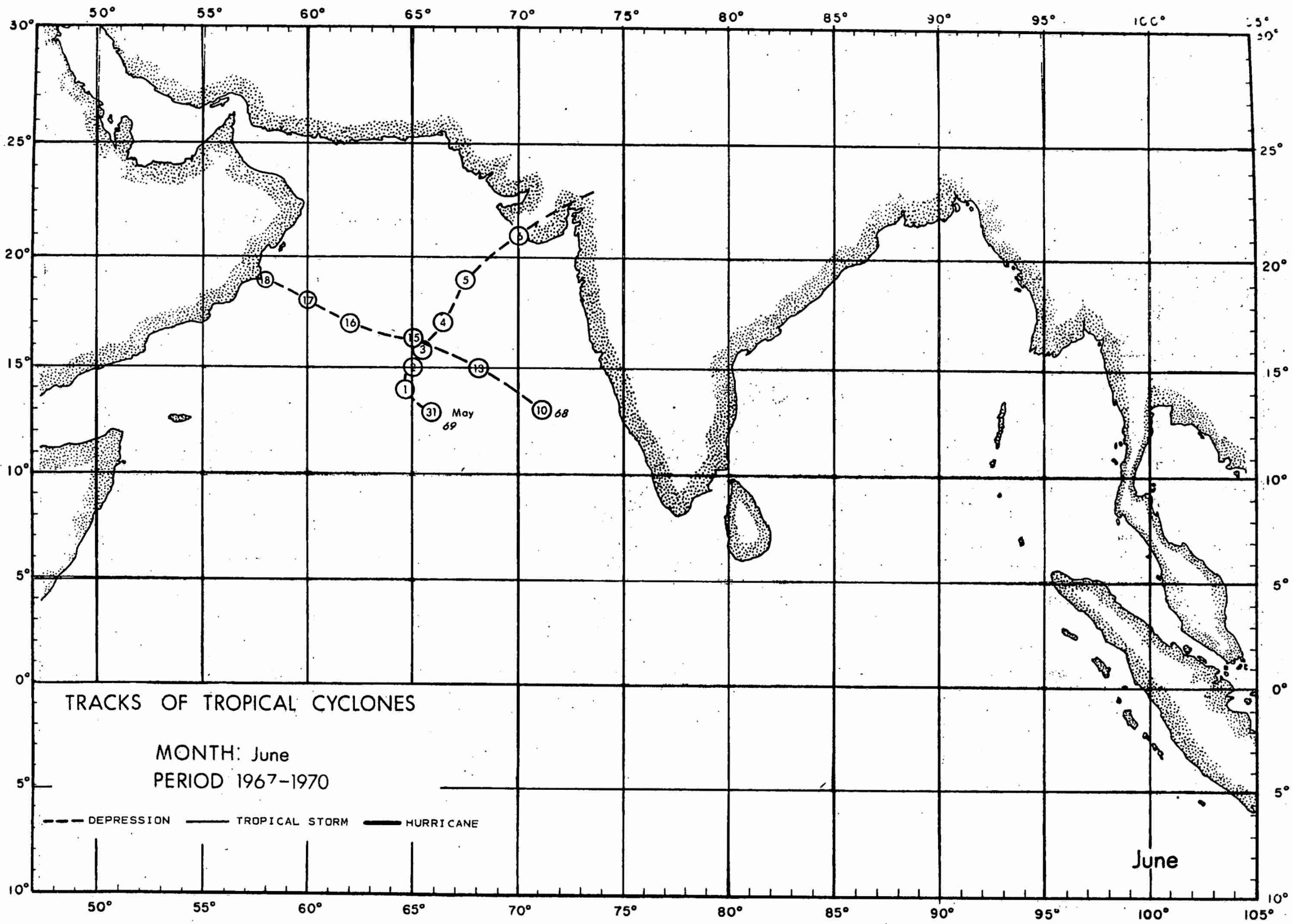

TRACKS OF TROPICAL CYCLONES
MONTH: June
PERIOD 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
June
May
69
68

Figure 7

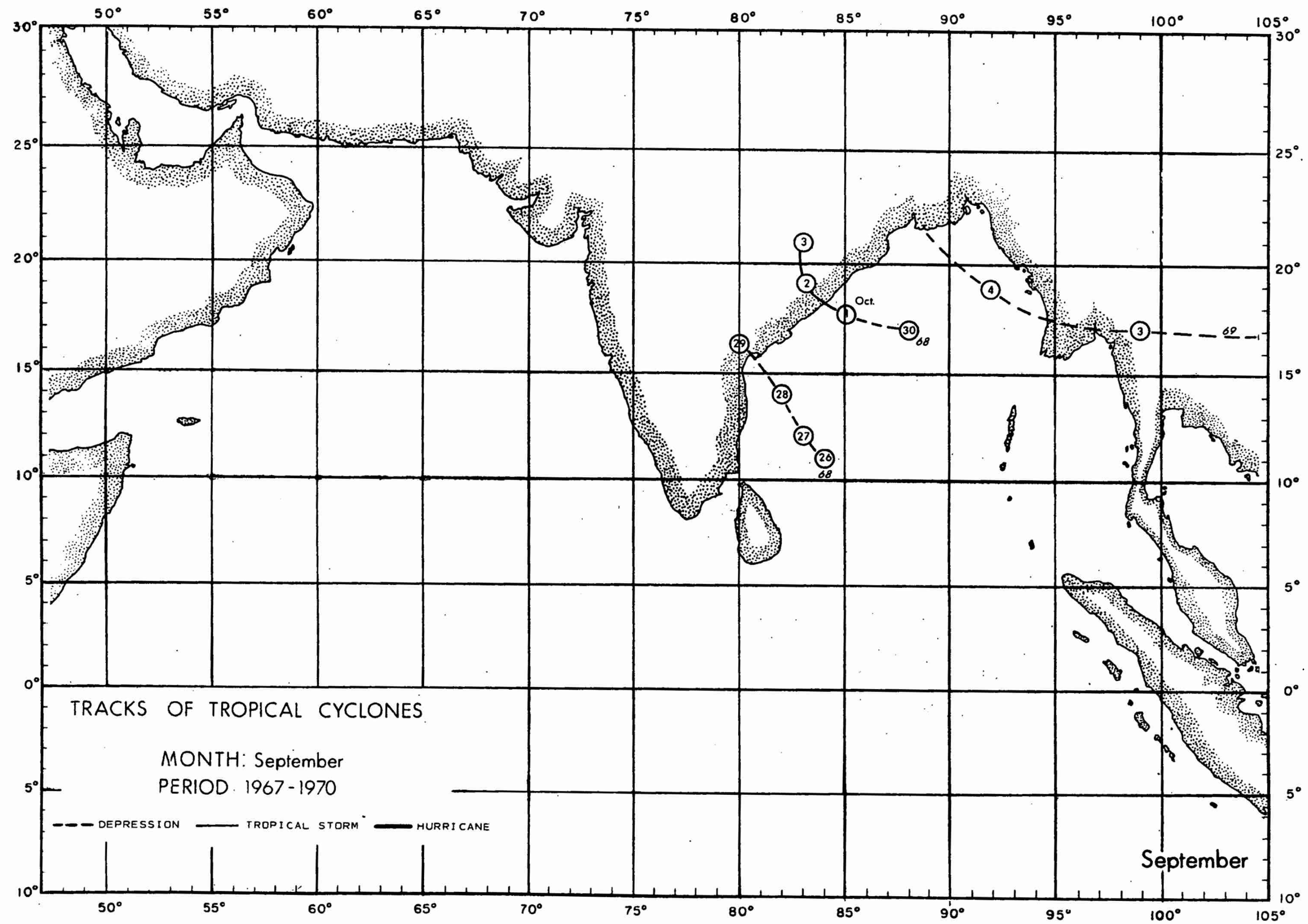

TRACKS OF TROPICAL CYCLONES
MONTH: September
PERIOD 1967-1970
DEPRESSION
TROPICAL STORM
HURRICANE
September
Oct.
68
69

Figure 8

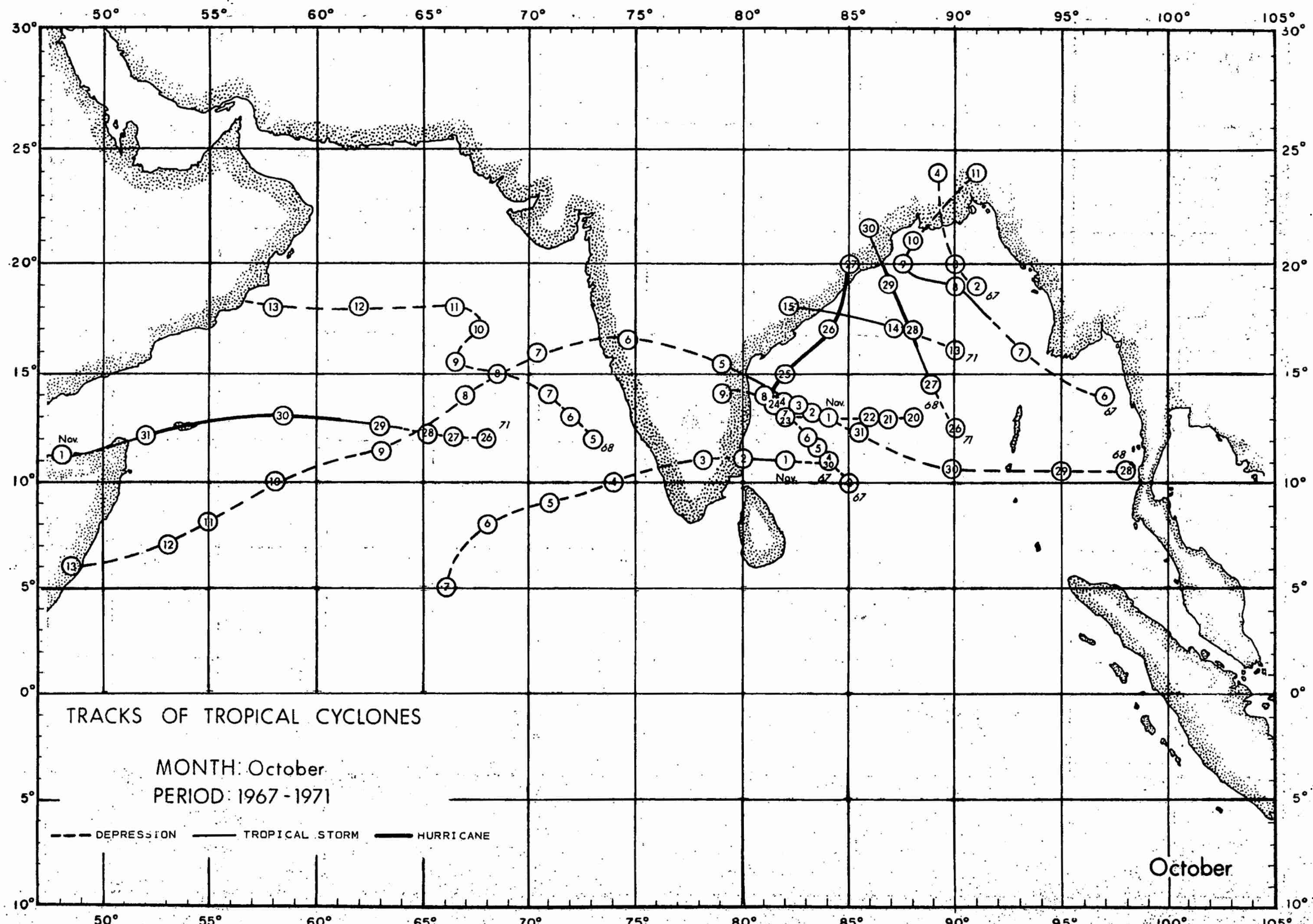

TRACKS OF TROPICAL CYCLONES
MONTH: October
PERIOD: 1967 - 1971
DEPRESSION
TROPICAL STORM
HURRICANE
October

Figure 9a

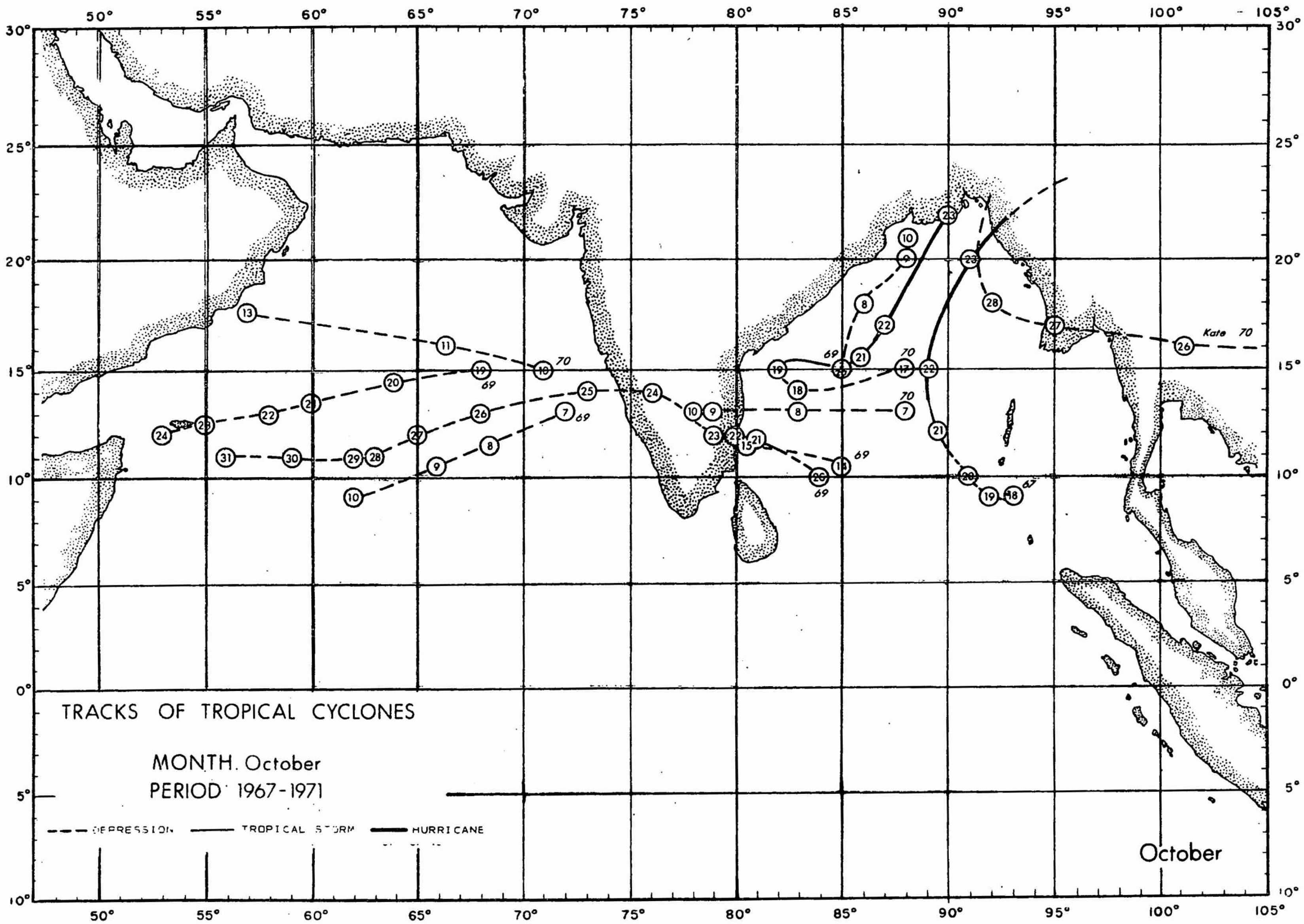

TRACKS OF TROPICAL CYCLONES
MONTH. October
PERIOD 1967-1971
HURRICANE
October
Kate 70

Figure 9b

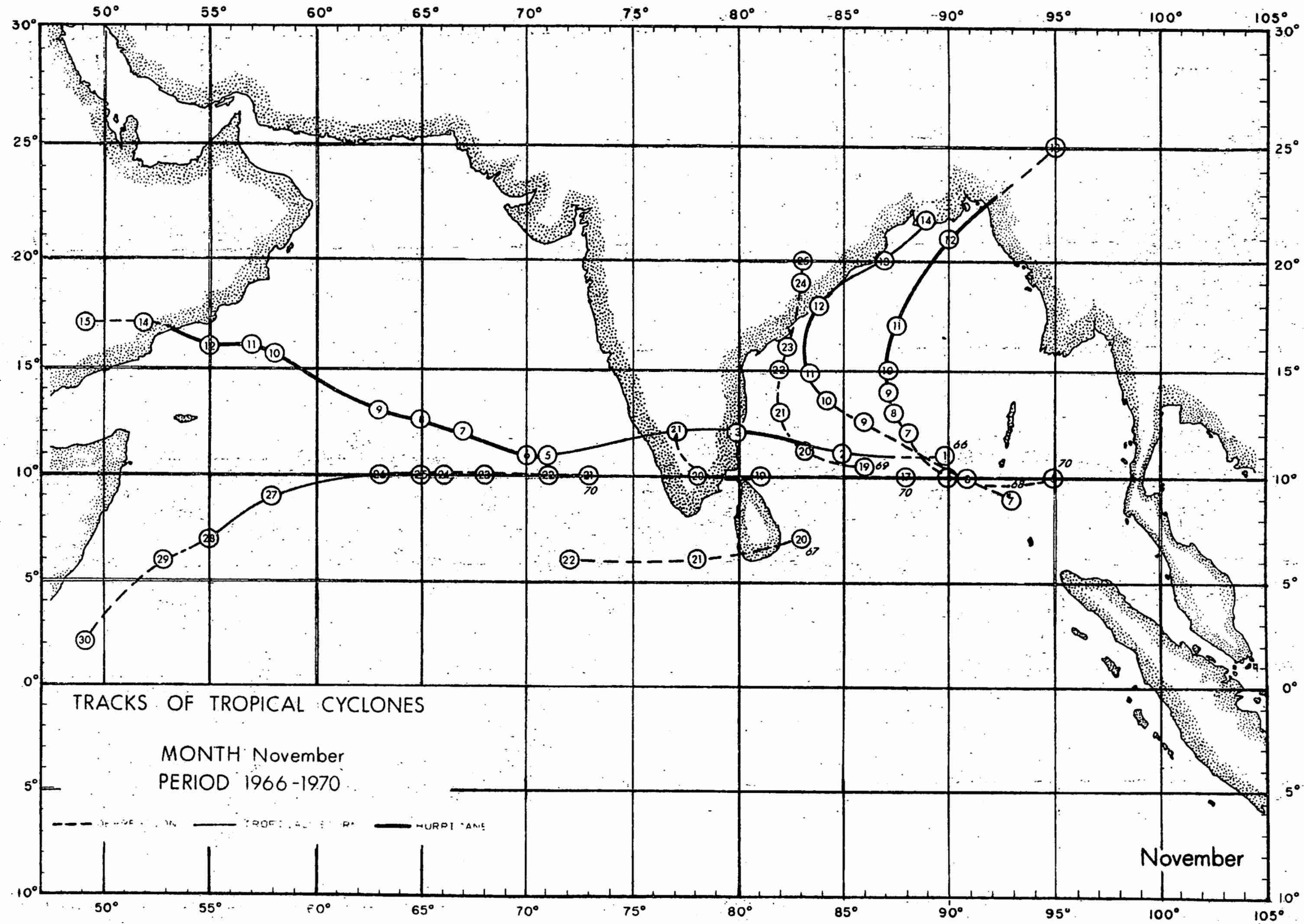

TRACKS OF TROPICAL CYCLONES
MONTH November
PERIOD 1966-1970
November

Figure 10a

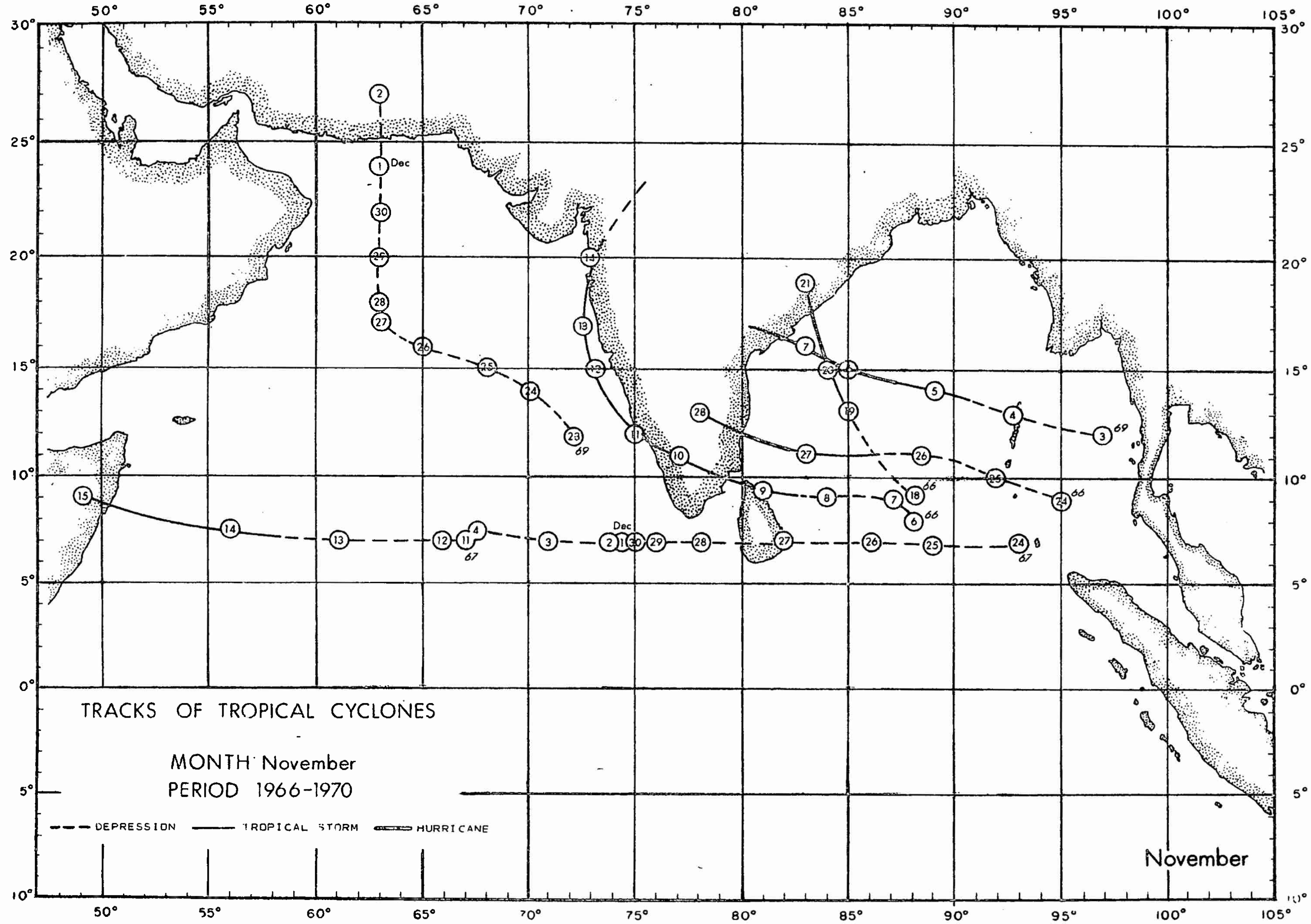

TRACKS OF TROPICAL CYCLONES
MONTH November
PERIOD 1966-1970
DEPRESSION
TROPICAL STORM
HURRICANE
November
Dec
Dec

Figure 10b

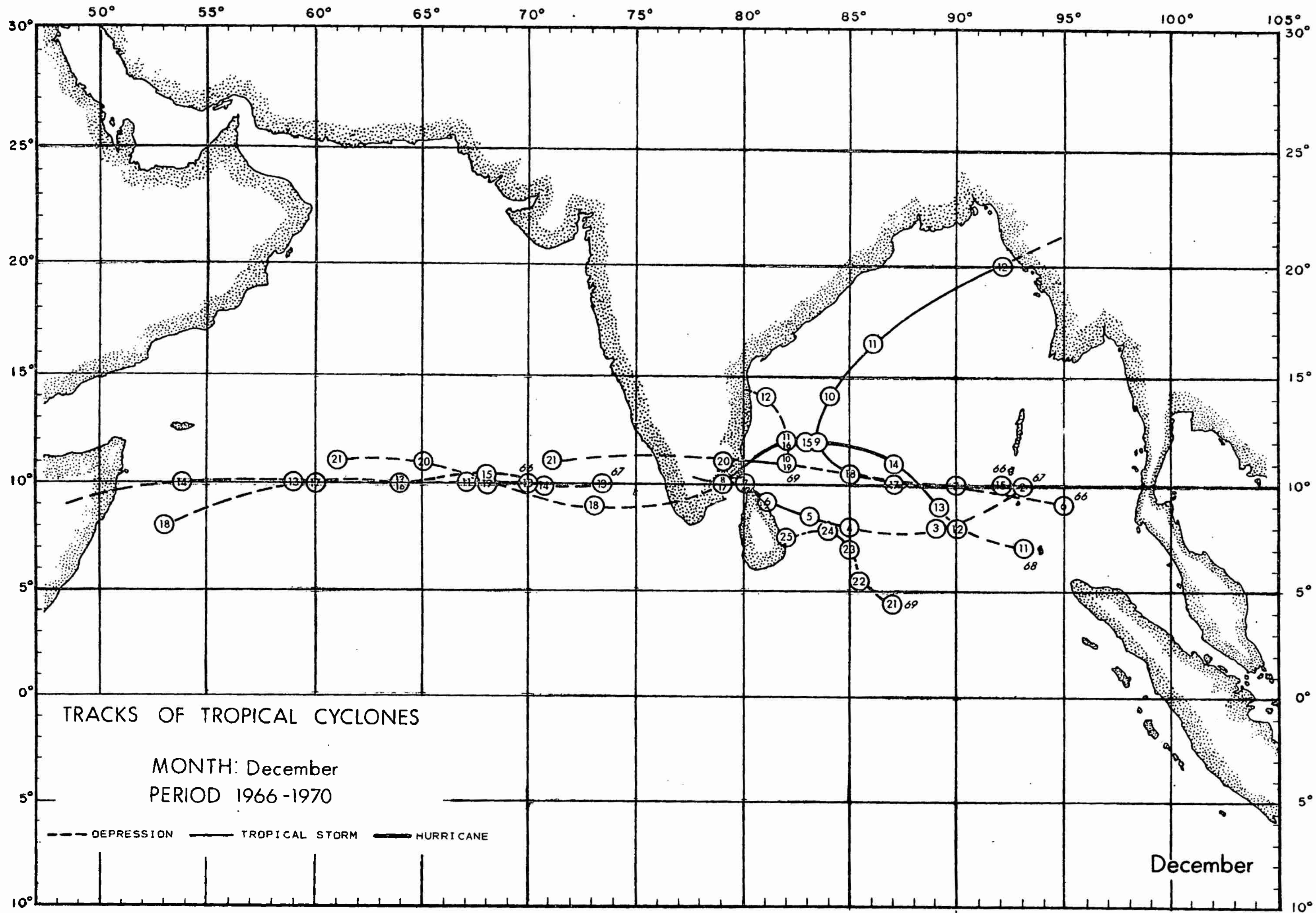

TRACKS OF TROPICAL CYCLONES
MONTH: December
PERIOD 1966-1970
DEPRESSION
TROPICAL STORM
HURRICANE
December

Figure 11

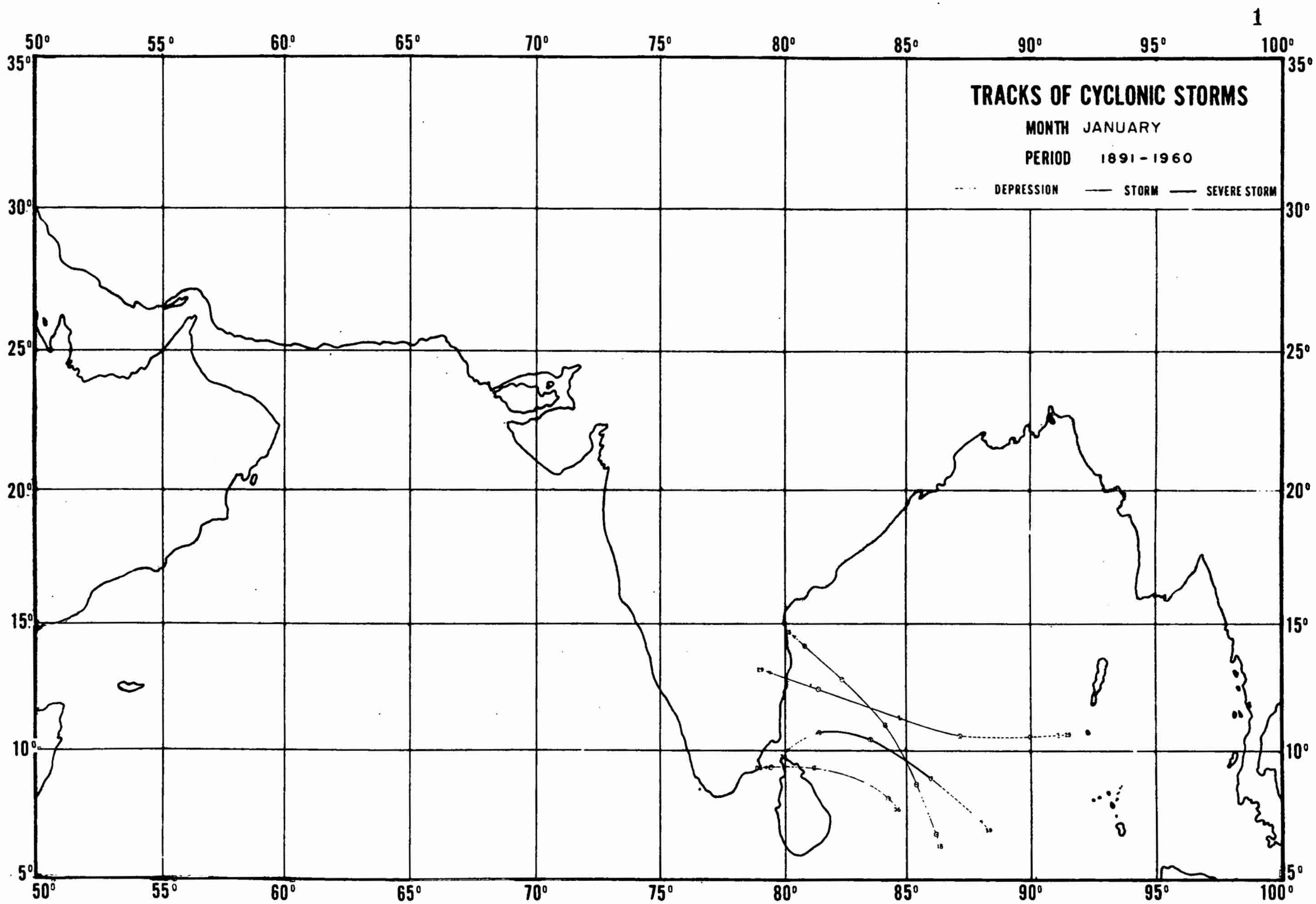

1
TRACKS OF CYCLONIC STORMS
MONTH JANUARY
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 12

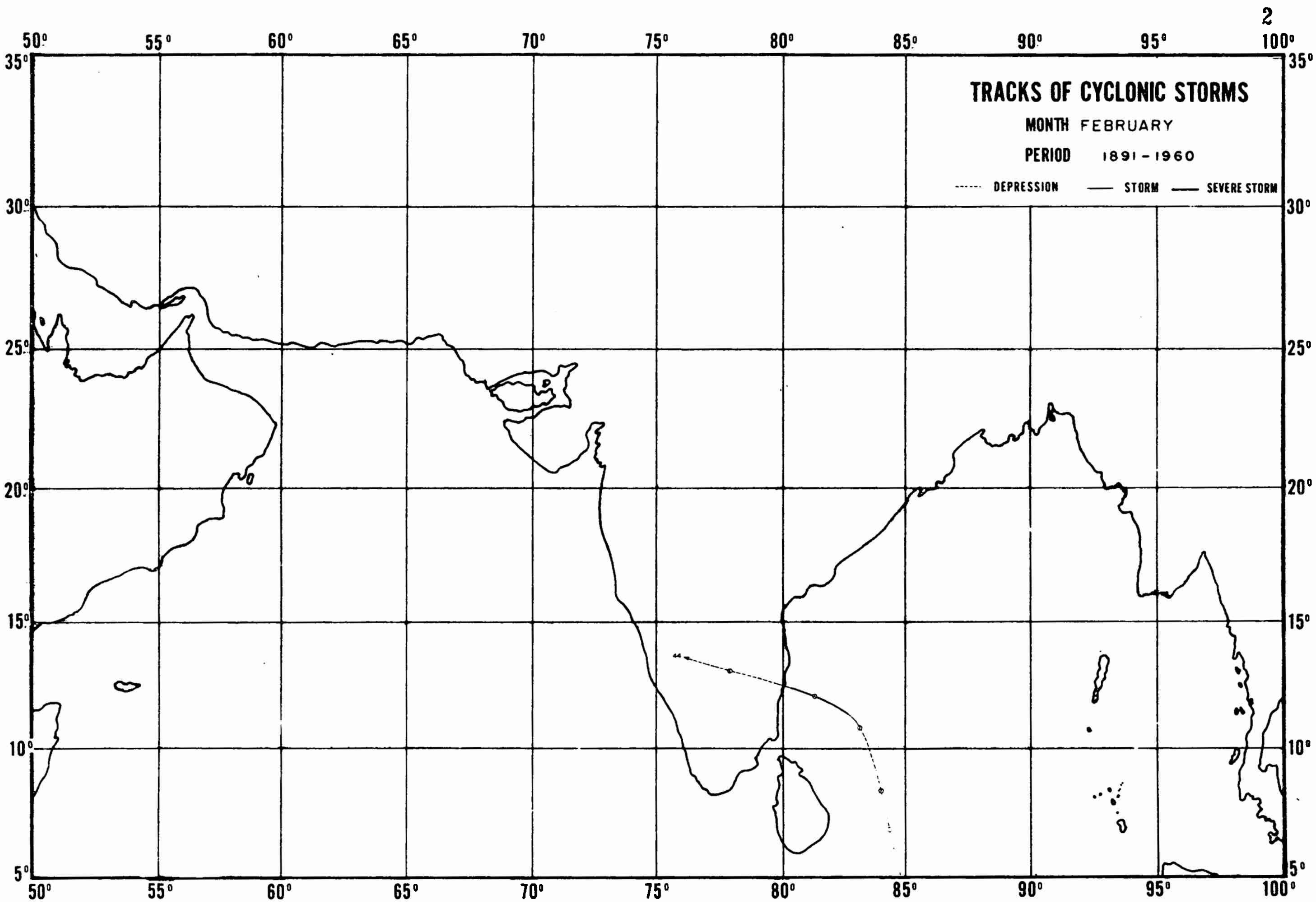
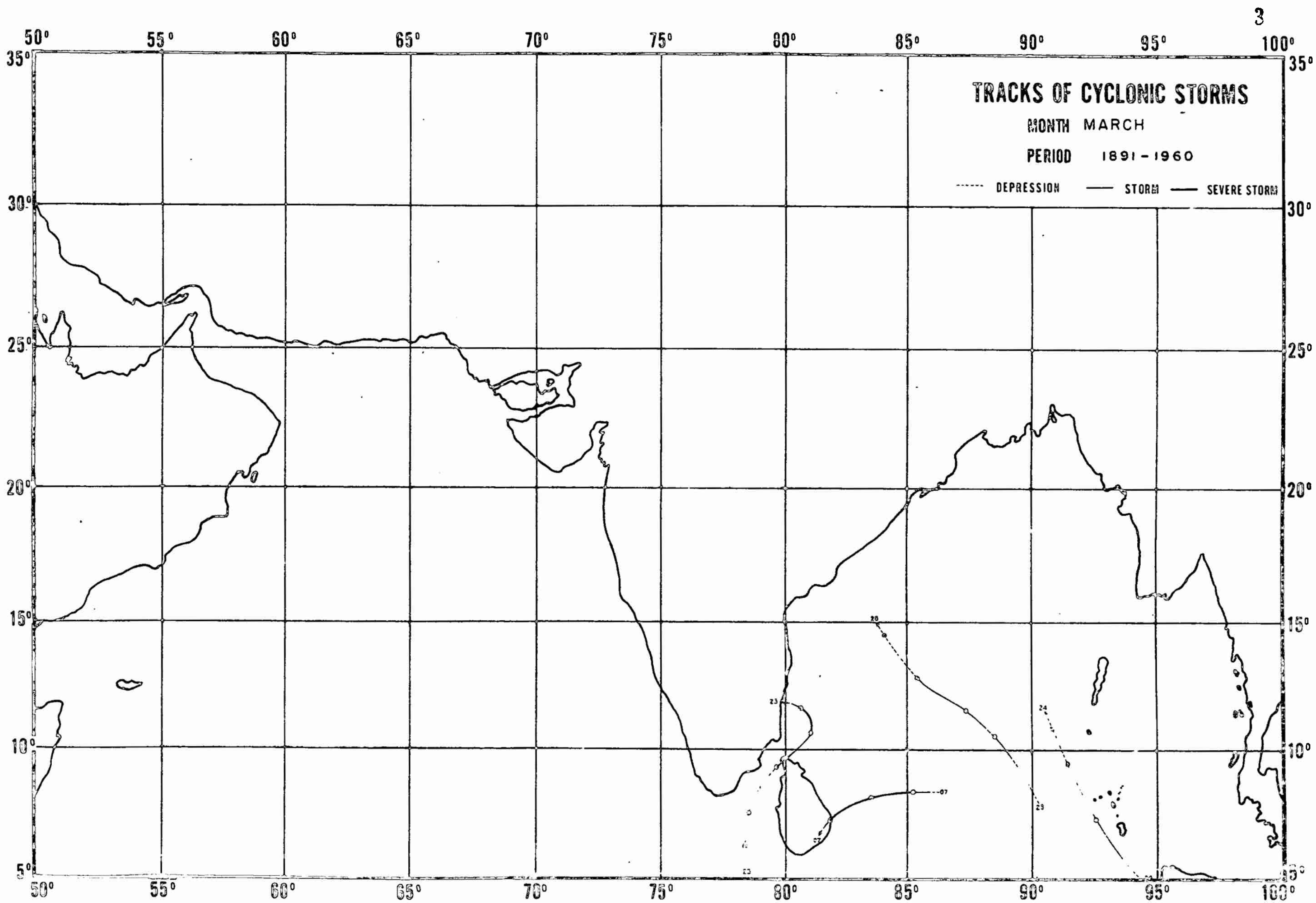

2
TRACKS OF CYCLONIC STORMS
MONTH FEBRUARY
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 13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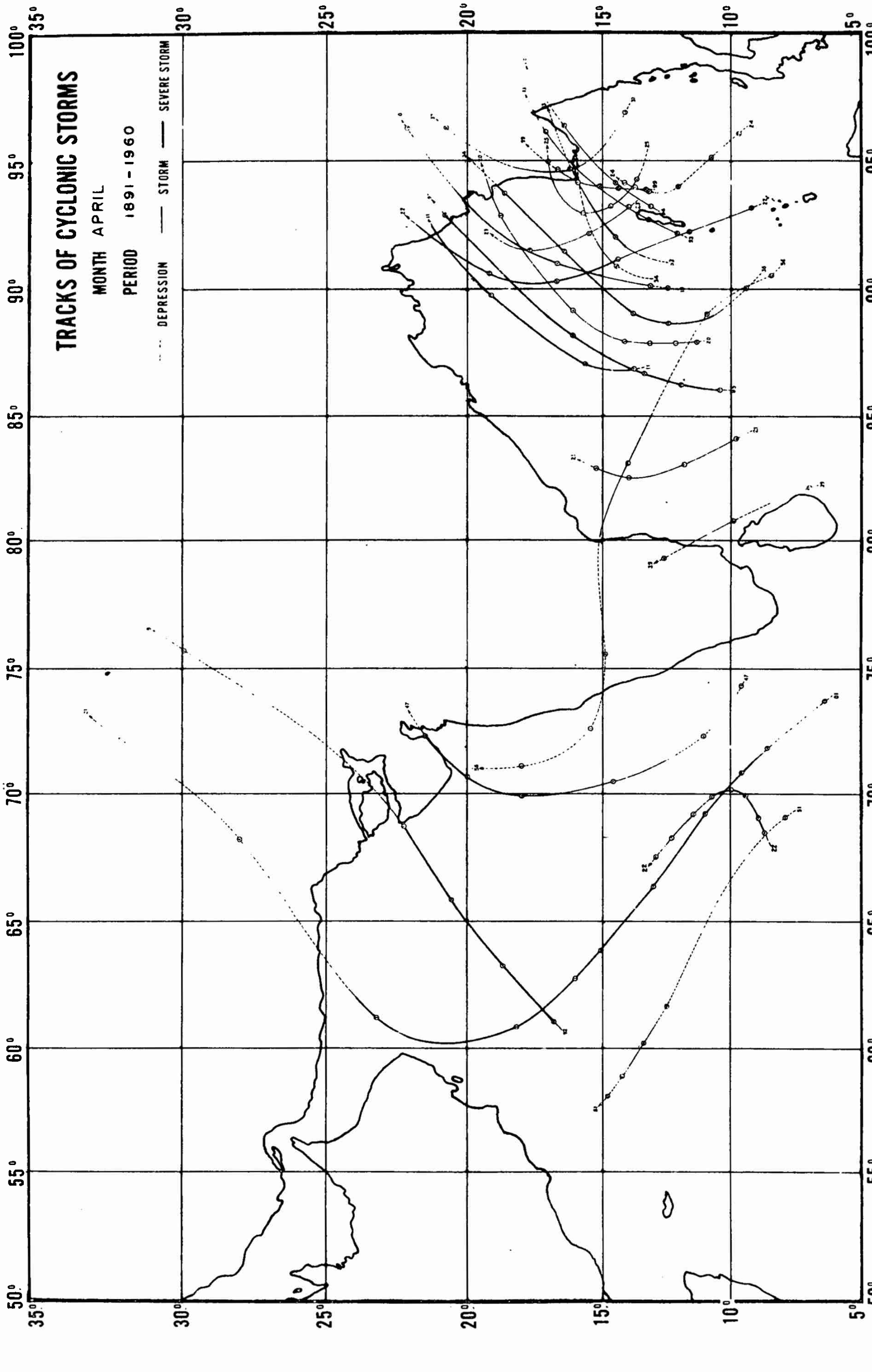
TRACKS OF CYCLONIC STORMS
MONTH MARCH
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 14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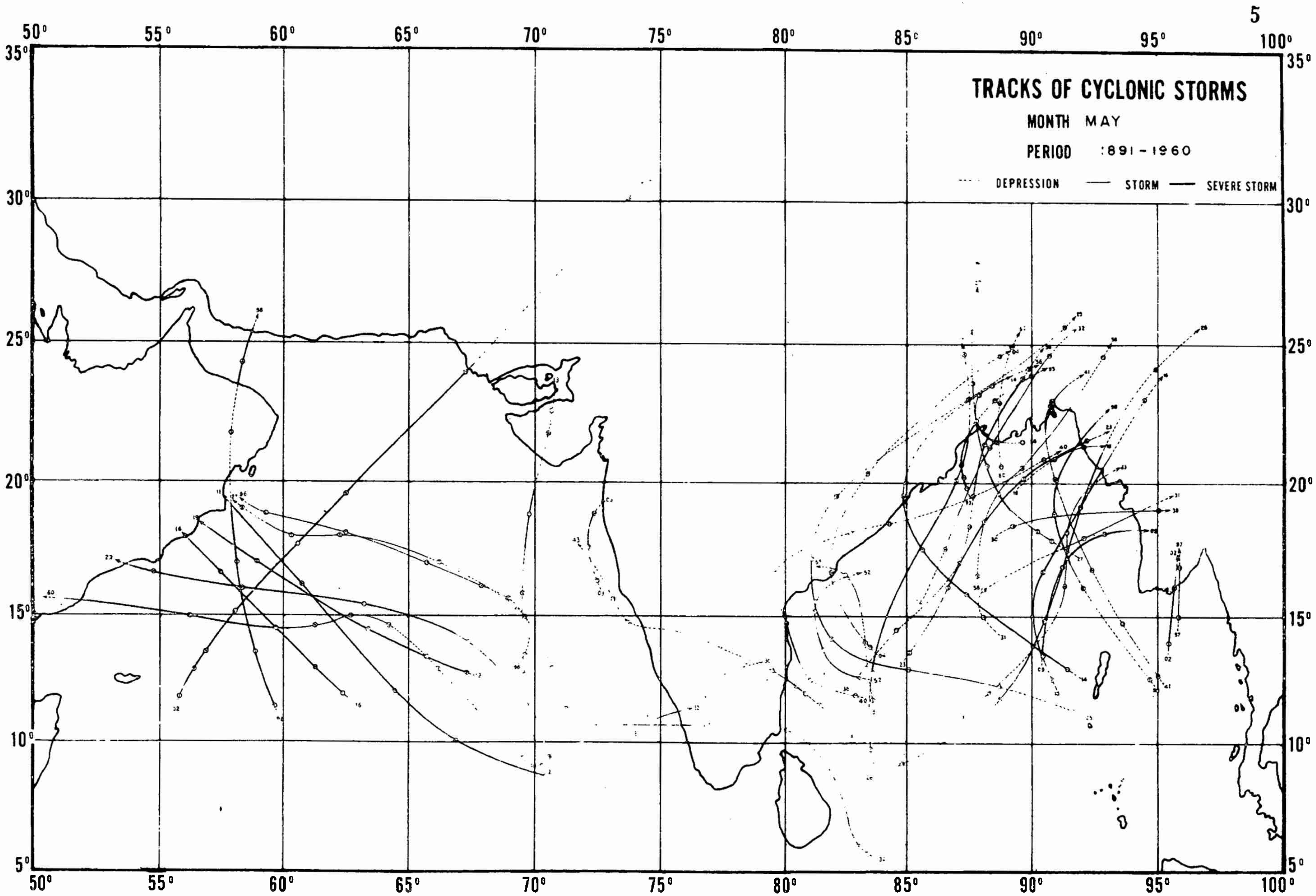
TRACKS OF CYCLONIC STORMS
MONTH APRIL
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM

Figure 15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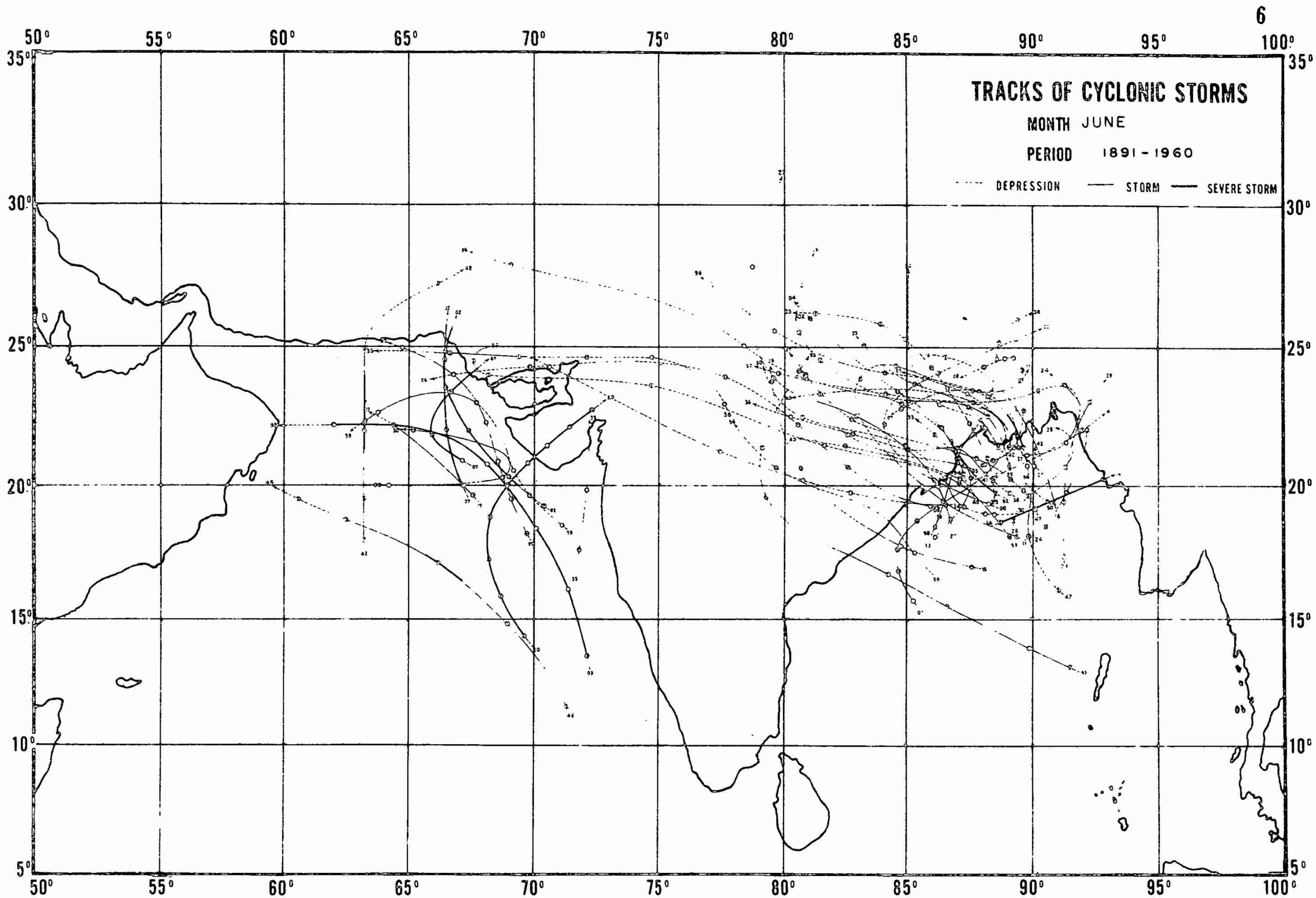
TRACKS OF CYCLONIC STORMS
MONTH MAY
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 16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TRACKS OF CYCLONIC STORMS
MONTH JUNE
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 17

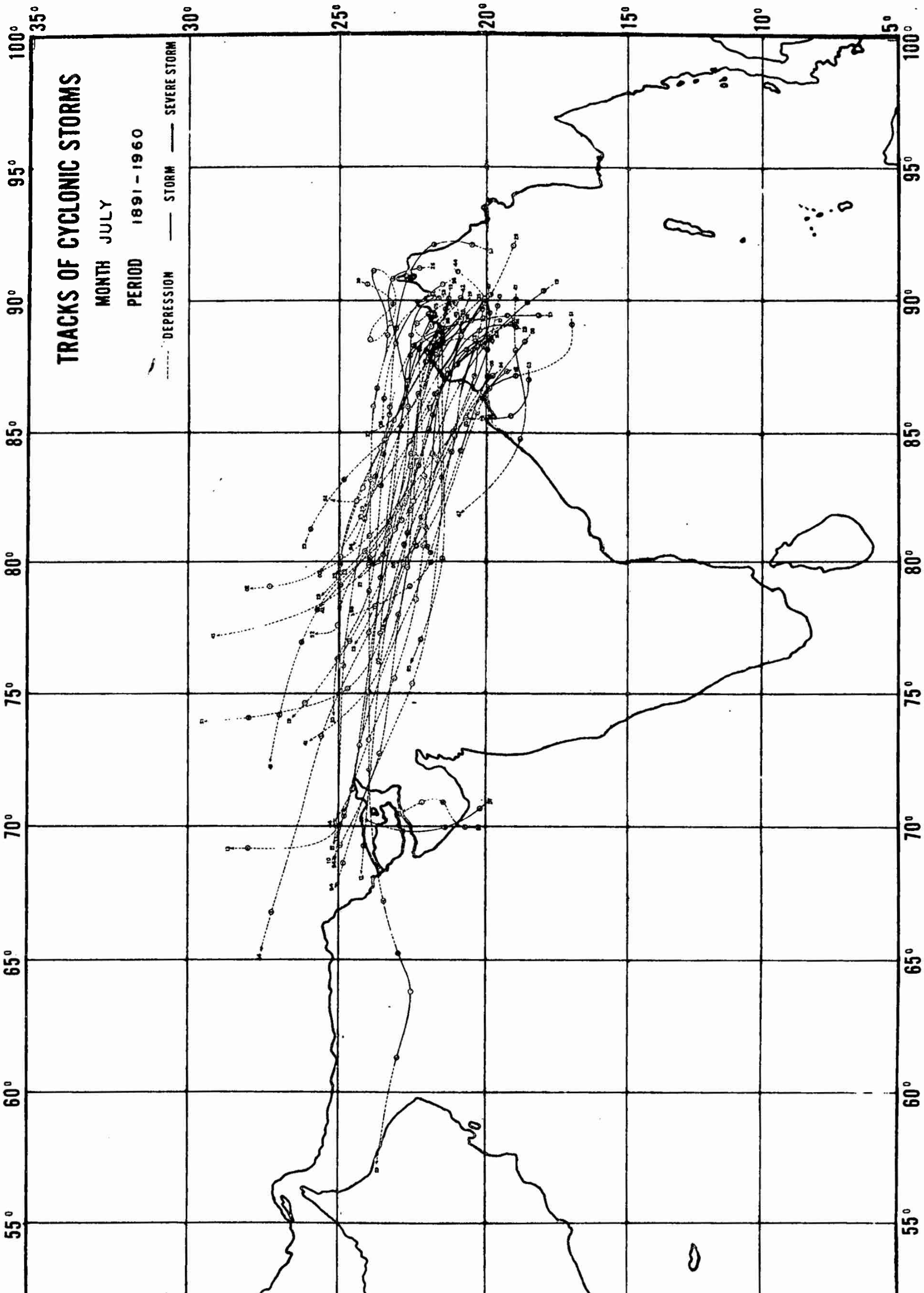
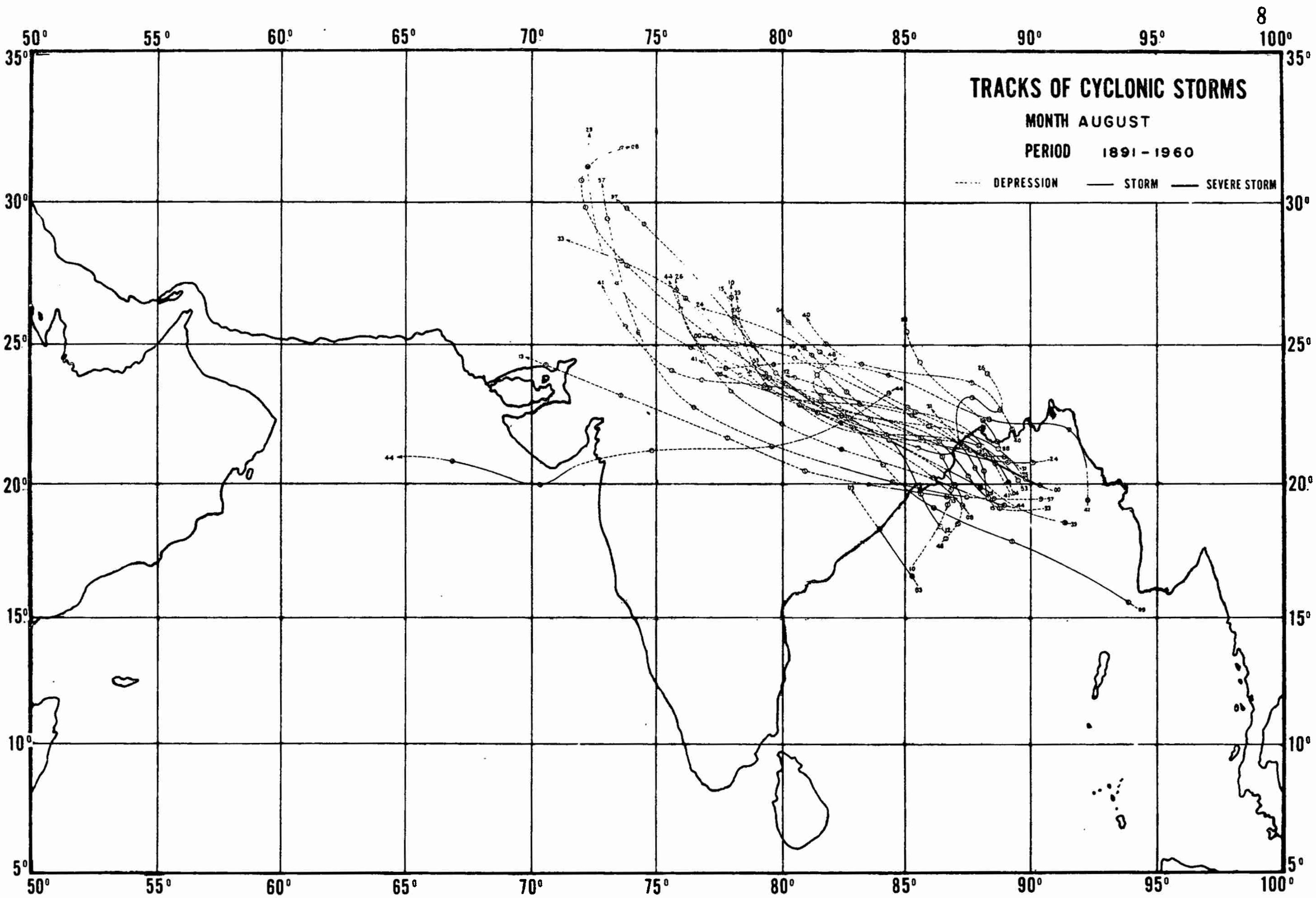

TRACKS OF CYCLONIC STORMS
MONTH JULY
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM

Figure 18


8
TRACKS OF CYCLONIC STORMS
MONTH AUGUST
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
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25°
20°
15°
10°
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Figure 19

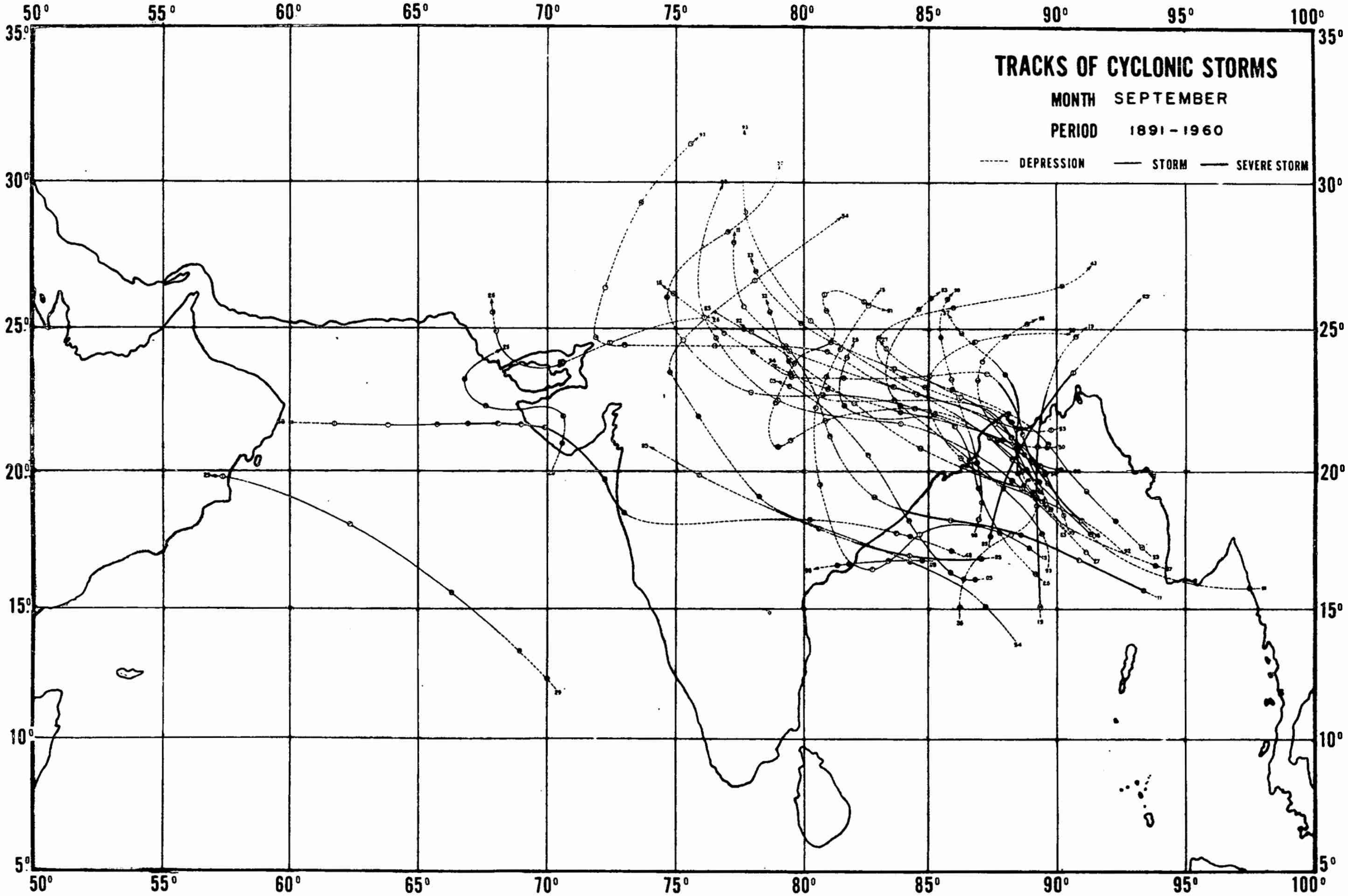
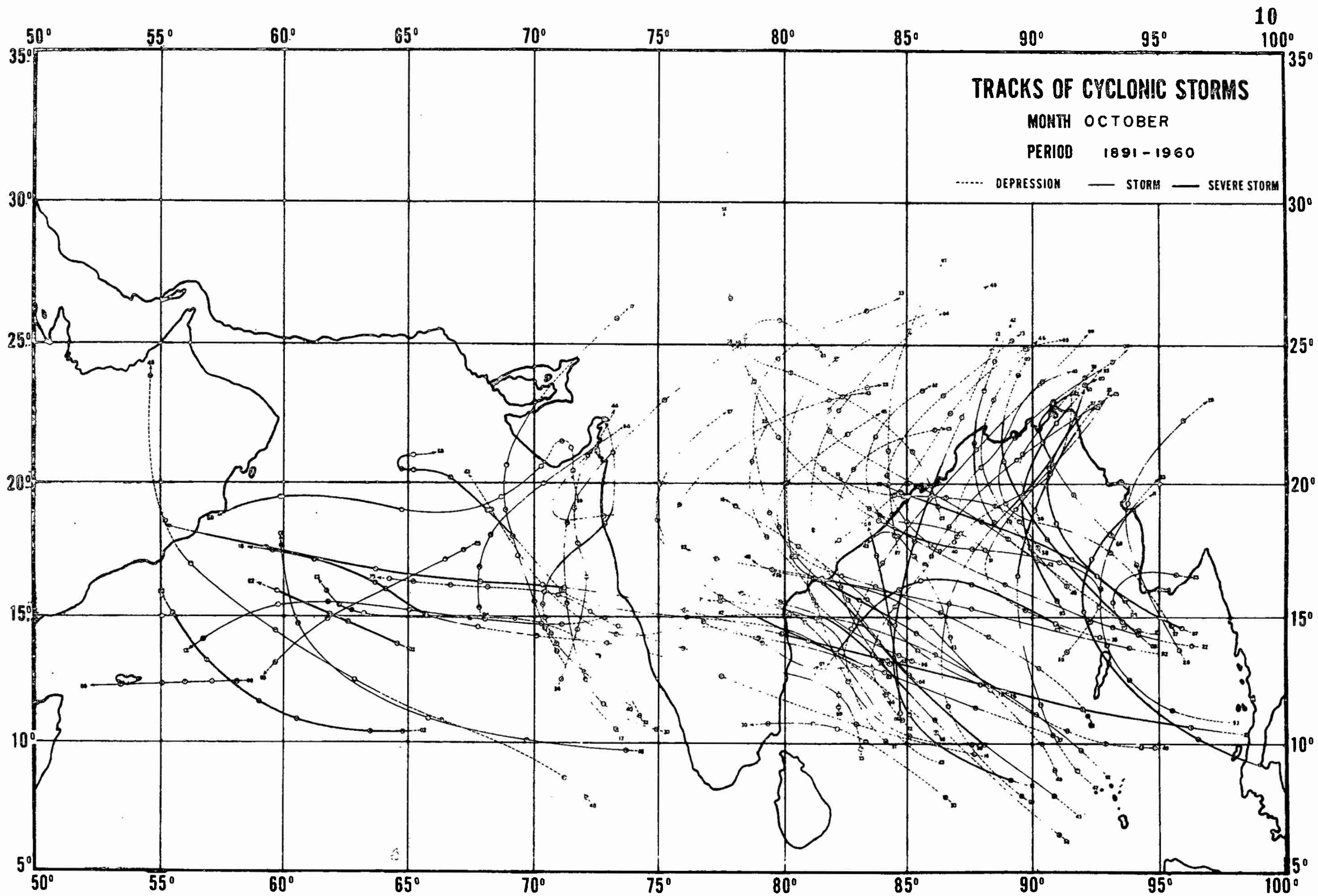

TRACKS OF CYCLONIC STORMS
MONTH SEPTEMBER
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure 20


10
TRACKS OF CYCLONIC STORMS
MONTH OCTOBER
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
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15°
10°
5°

Figure 21

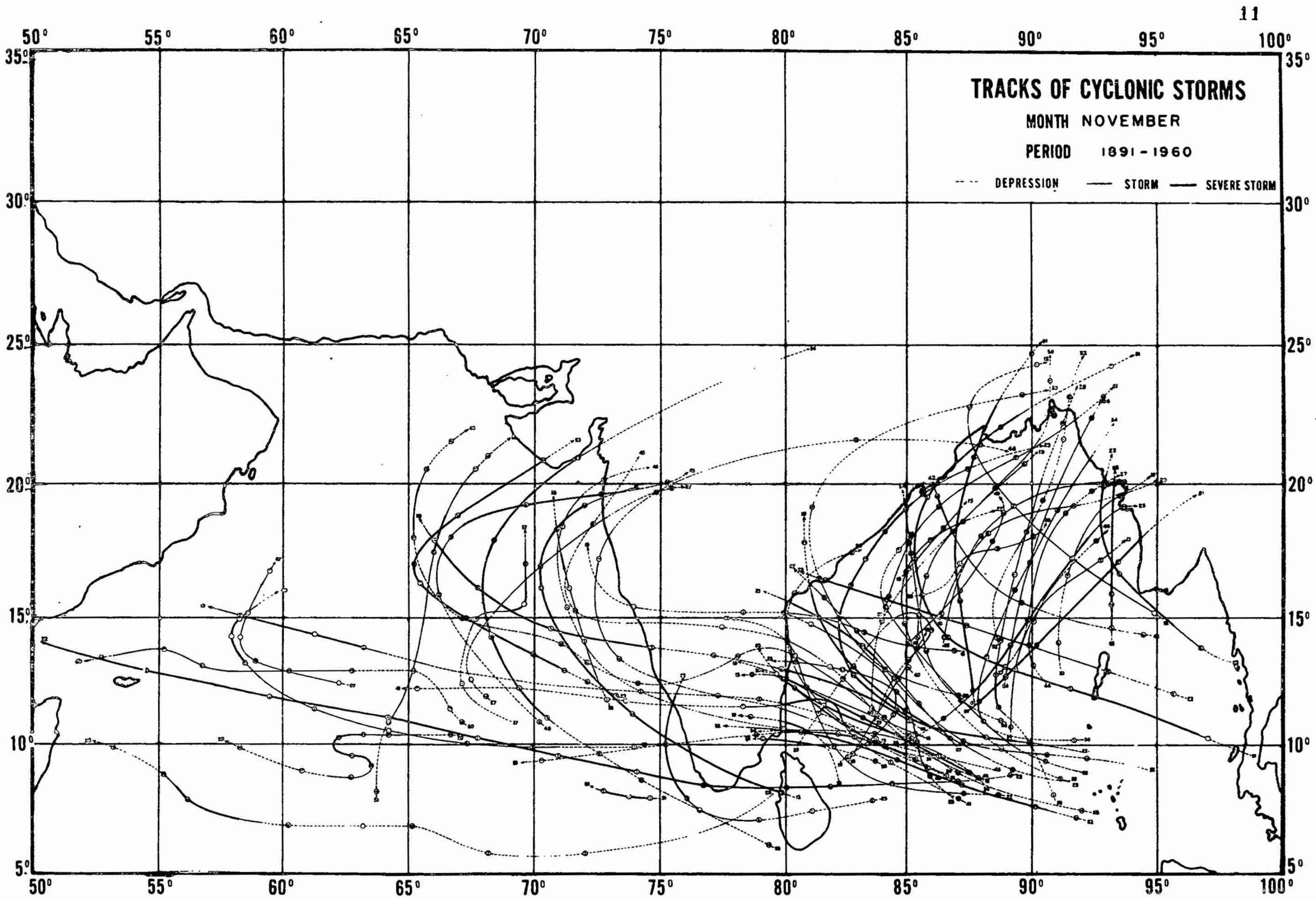
11
TRACKS OF CYCLONIC STORMS
MONTH NOVEMBER
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
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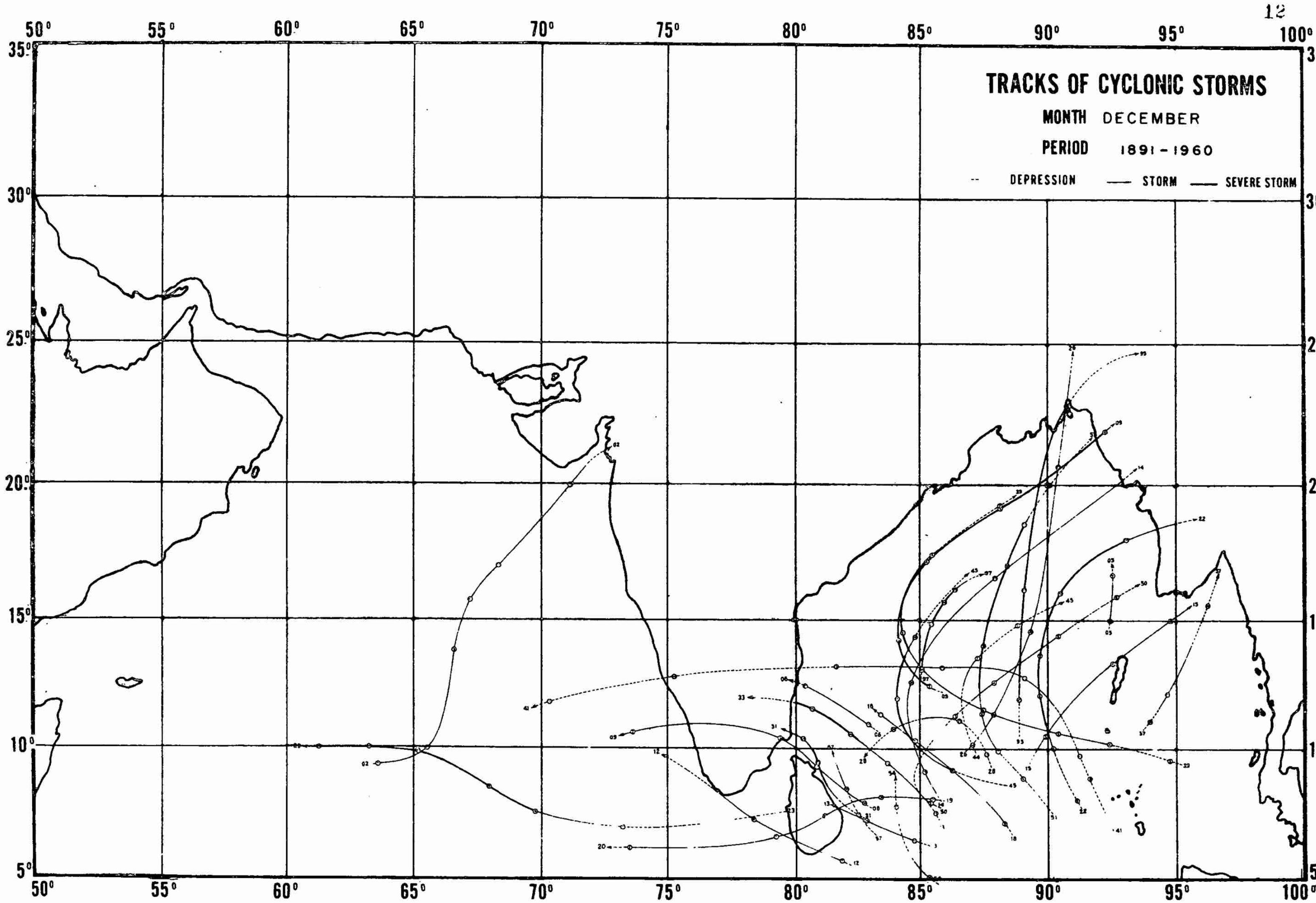
Figure 22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TRACKS OF CYCLONIC STORMS
MONTH DECEMBER
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM

Figure 23

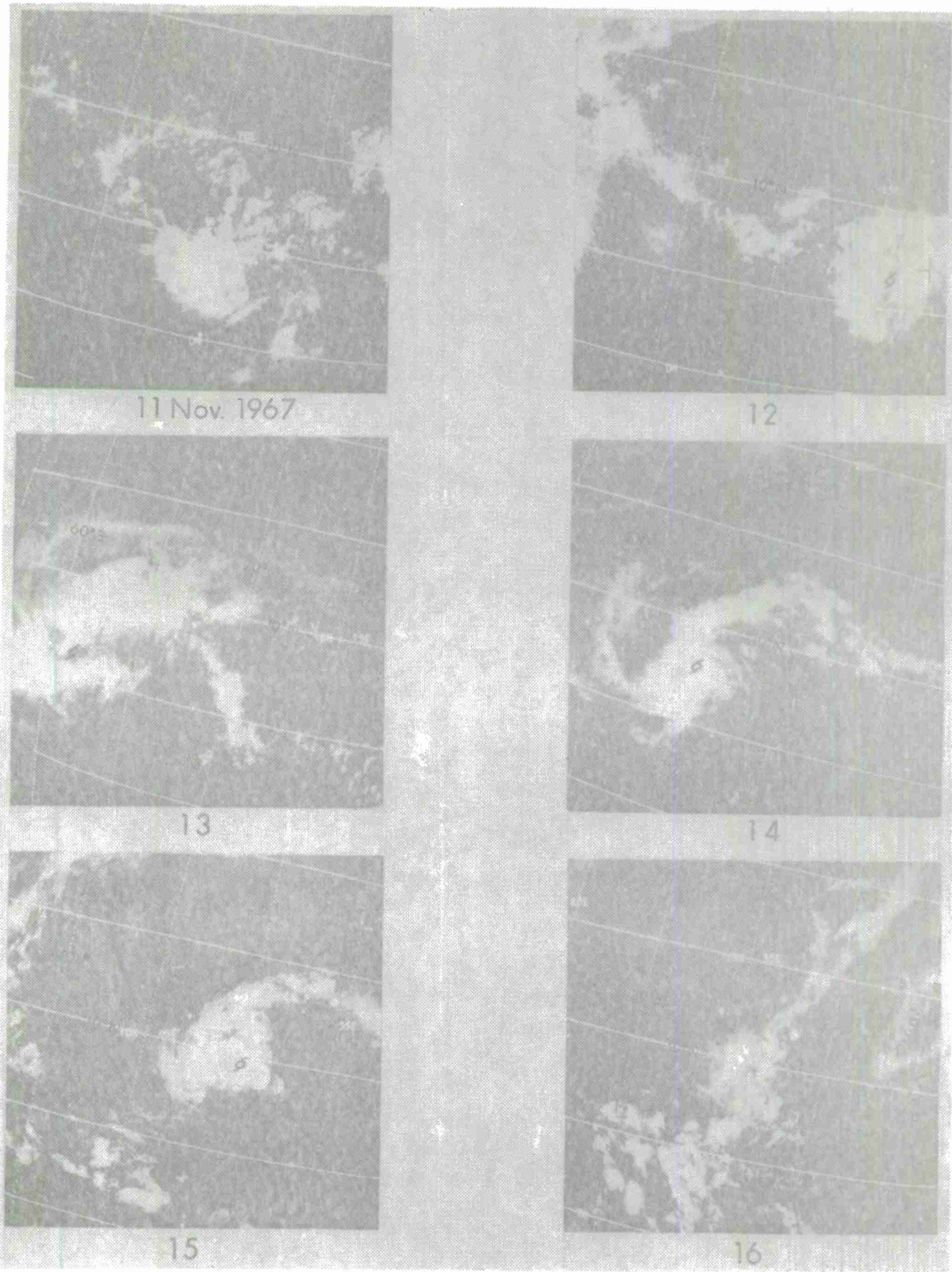


Figure 24. Satellite views of a tropical storm in the southwestern Arabian Sea (November 1967).

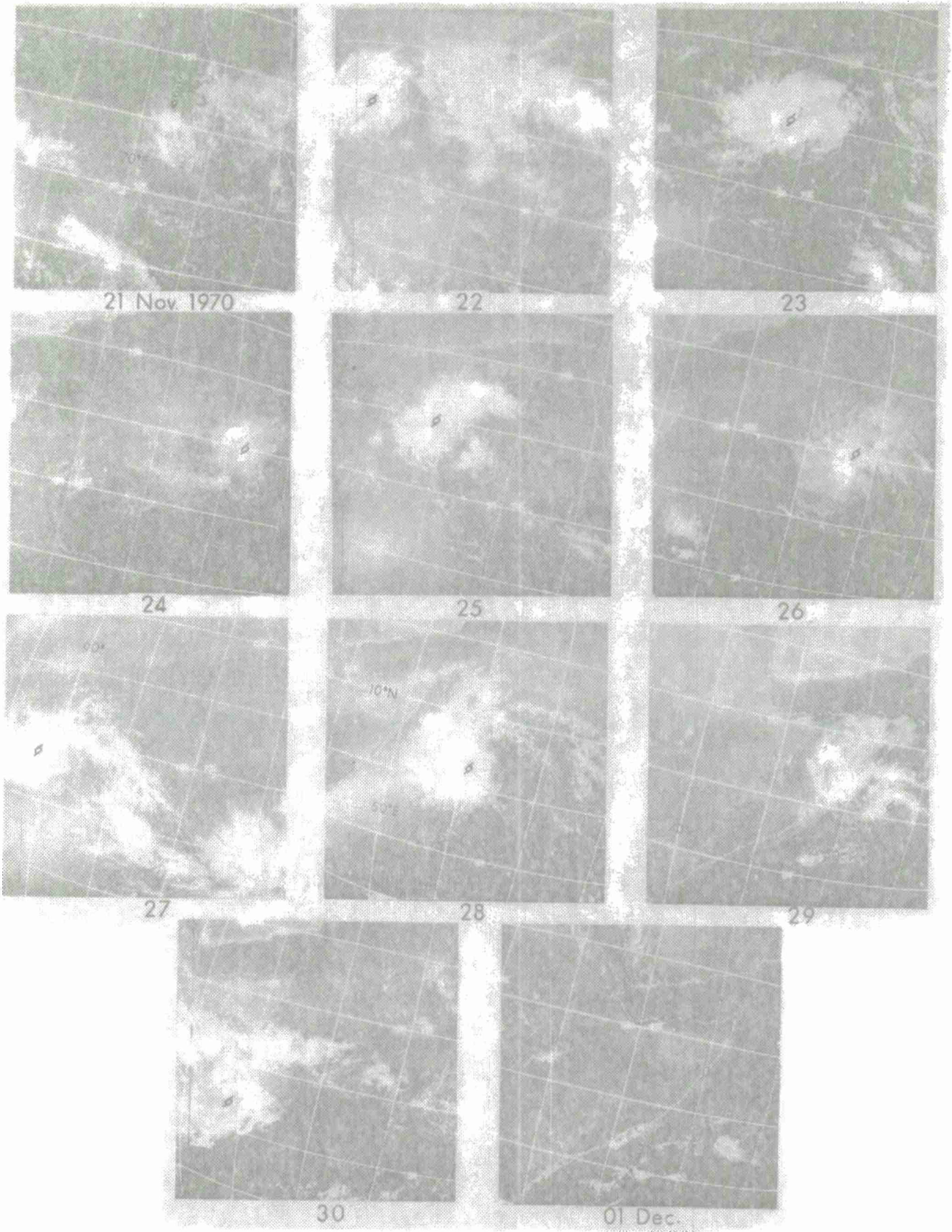
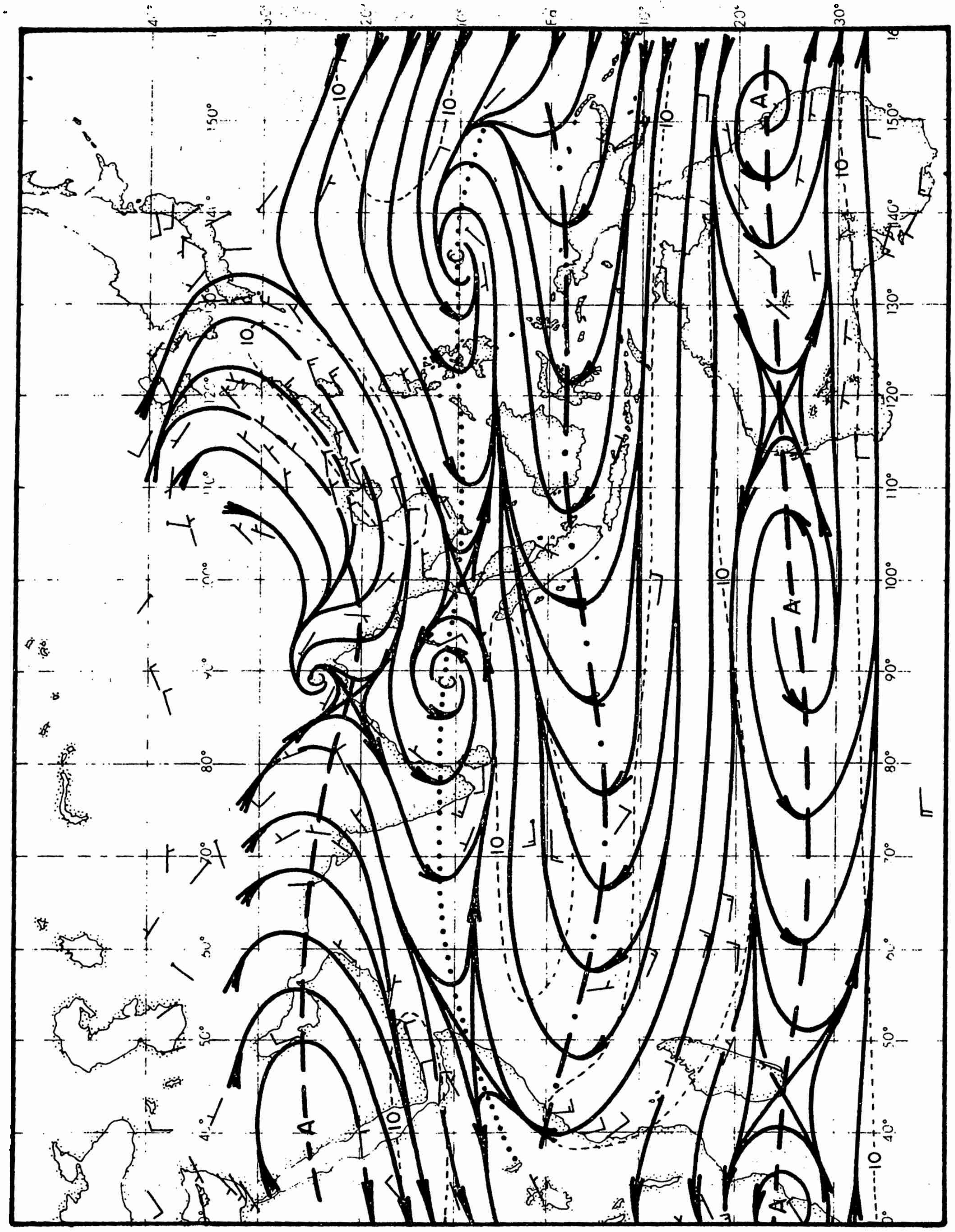
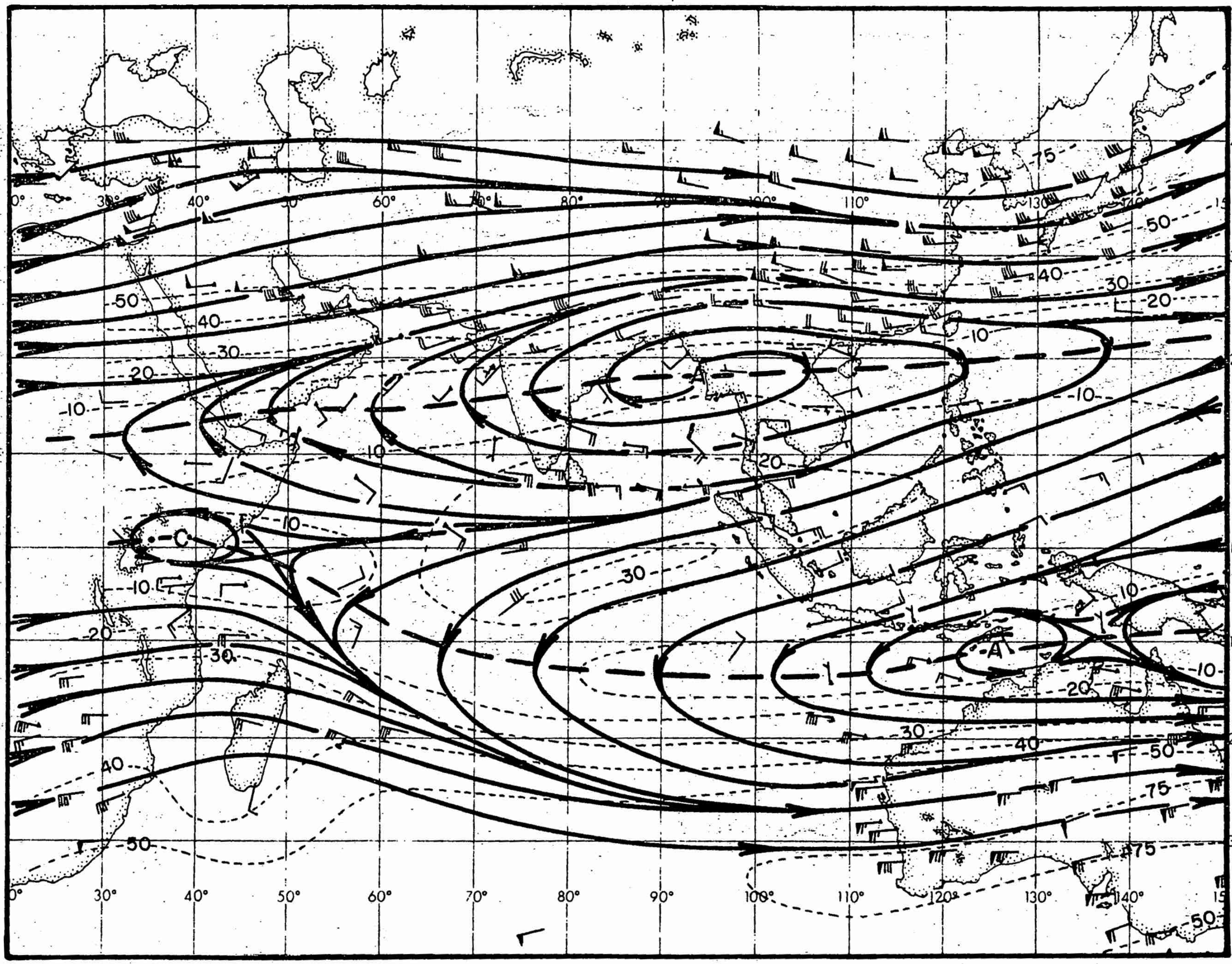


Figure 25. Satellite views of a tropical storm in the southwestern Arabian Sea (November 1970)

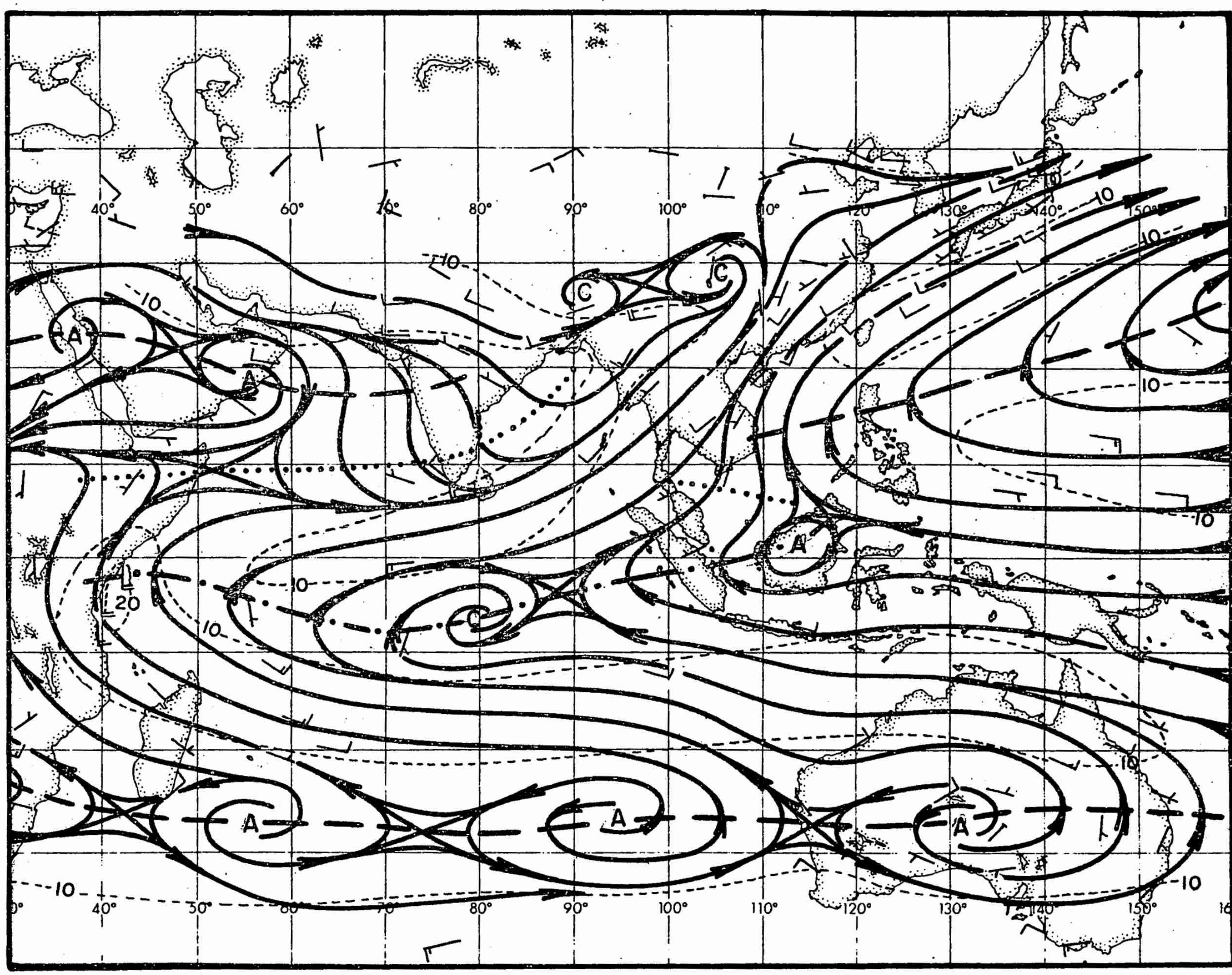


OCTOBER, 850 mb
Figure 26



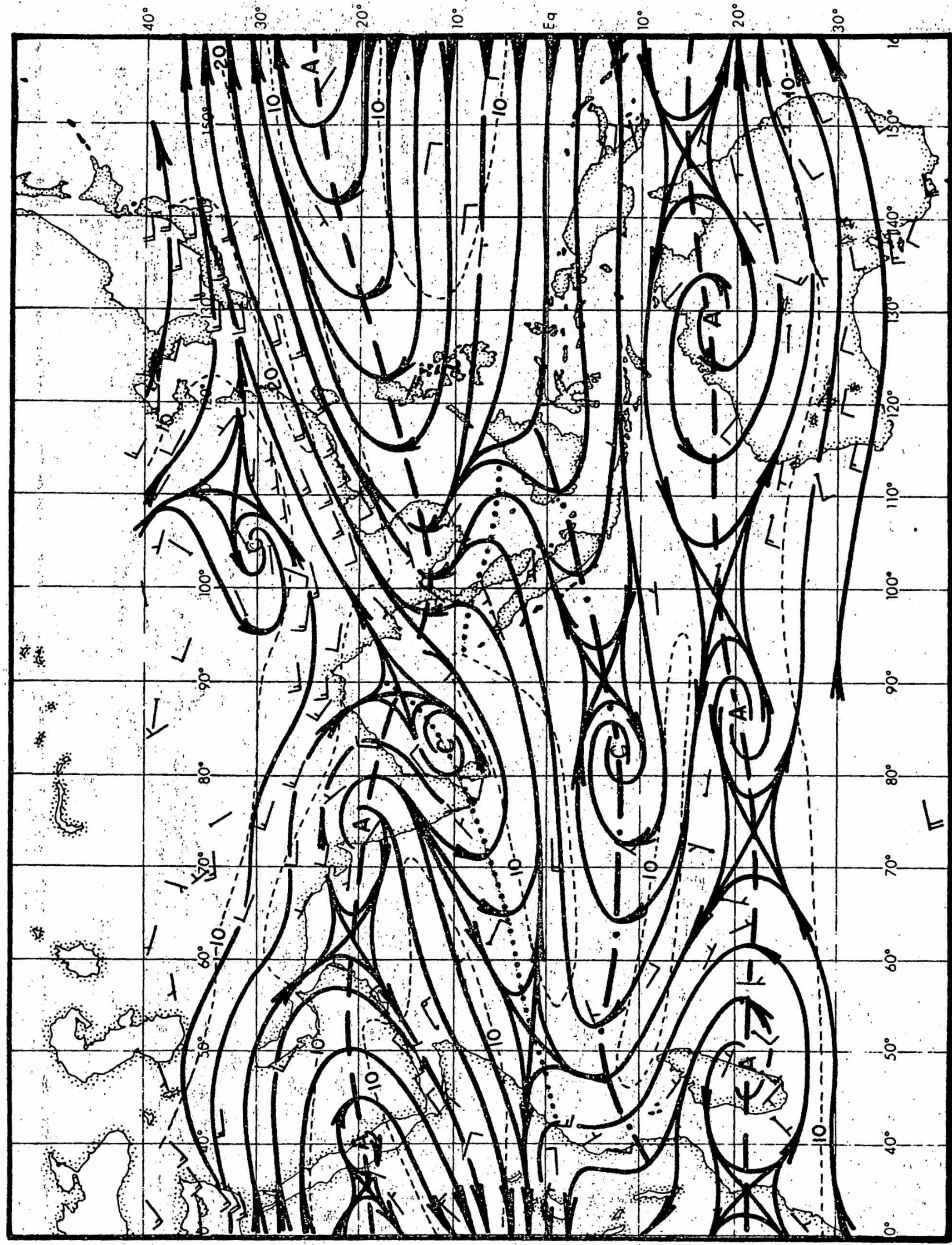
OCTOBER, 200 mb

Figure 27

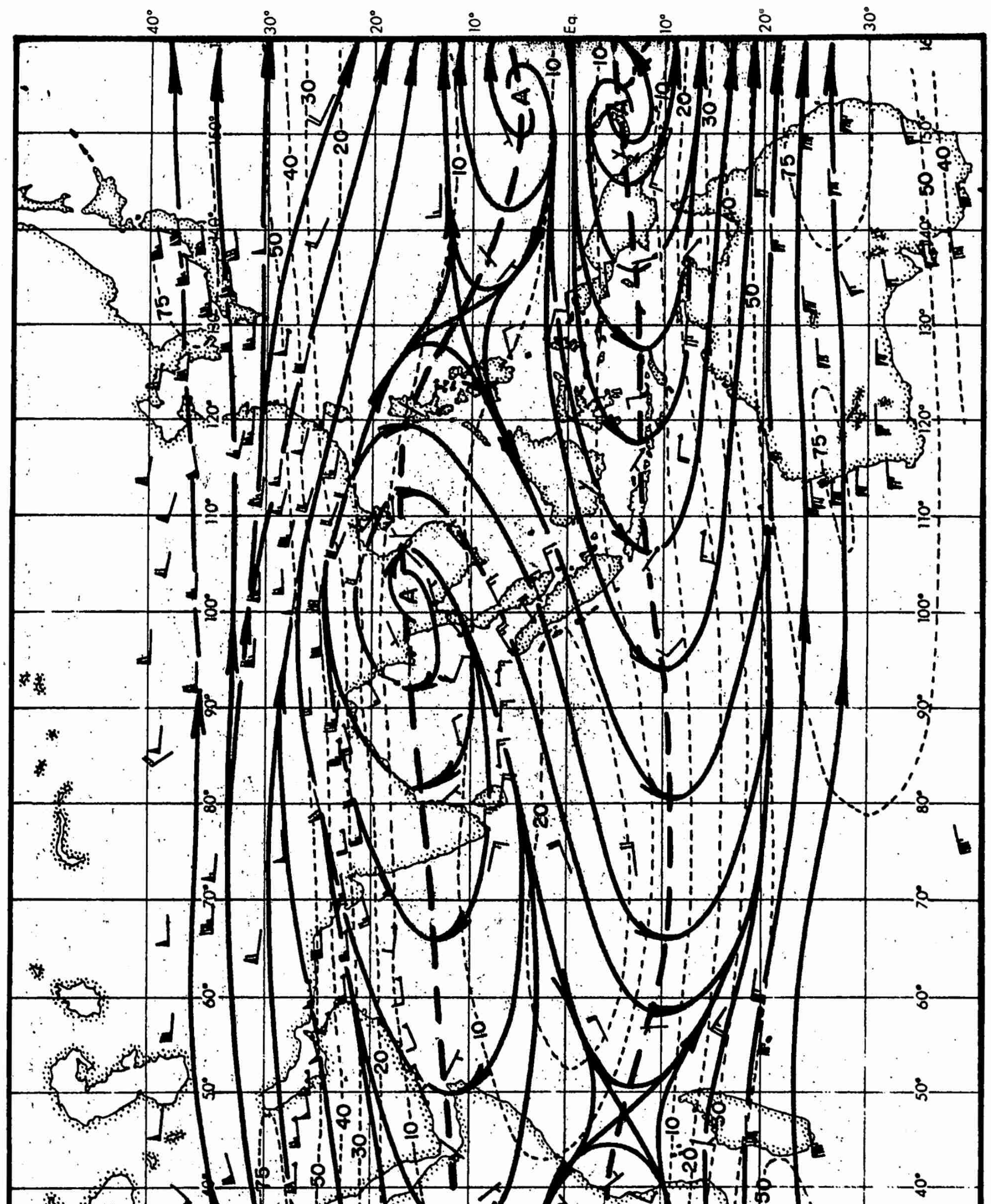


MAY, 850 mb

Figure 28

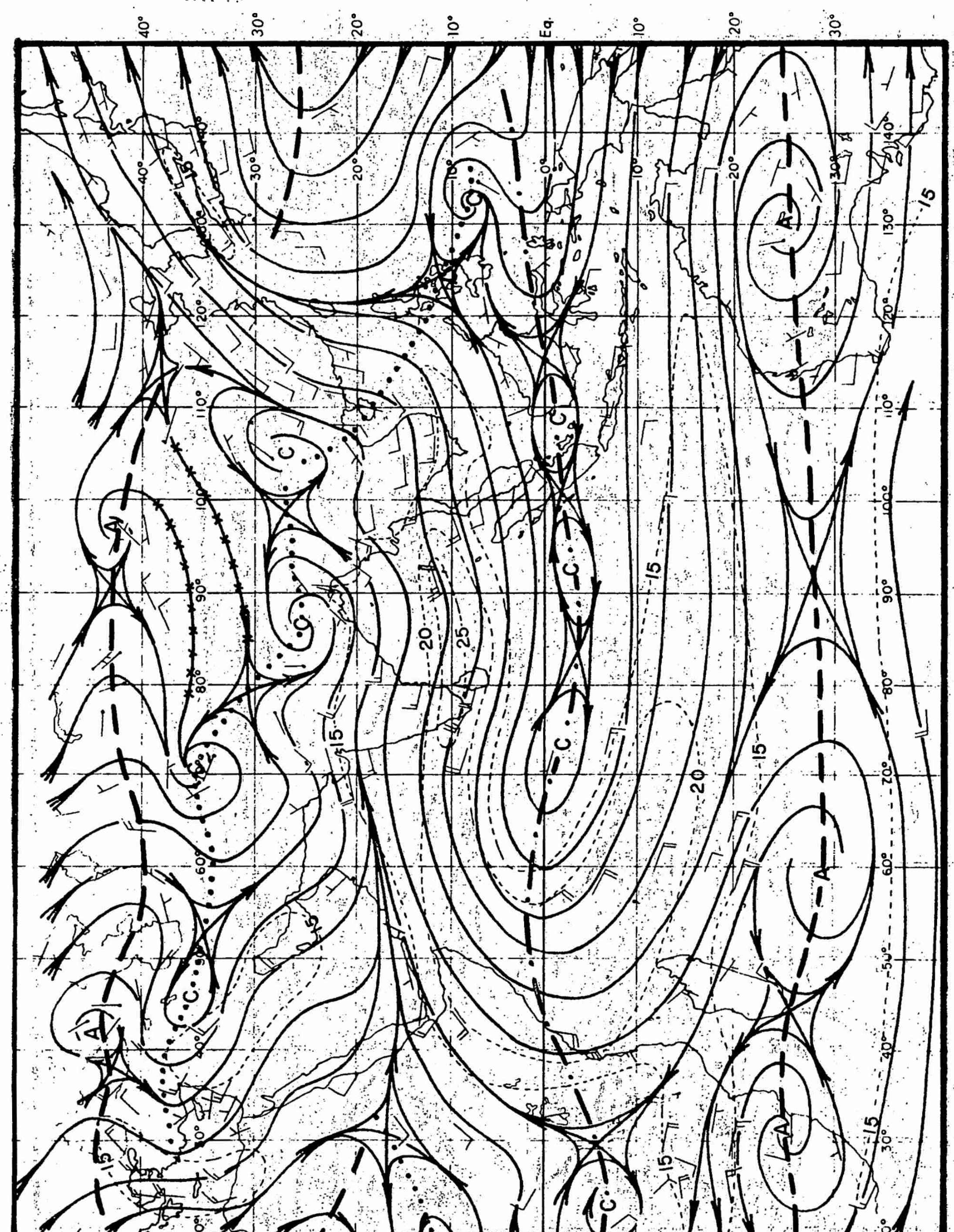


MAY, 700 mb
Figure 29

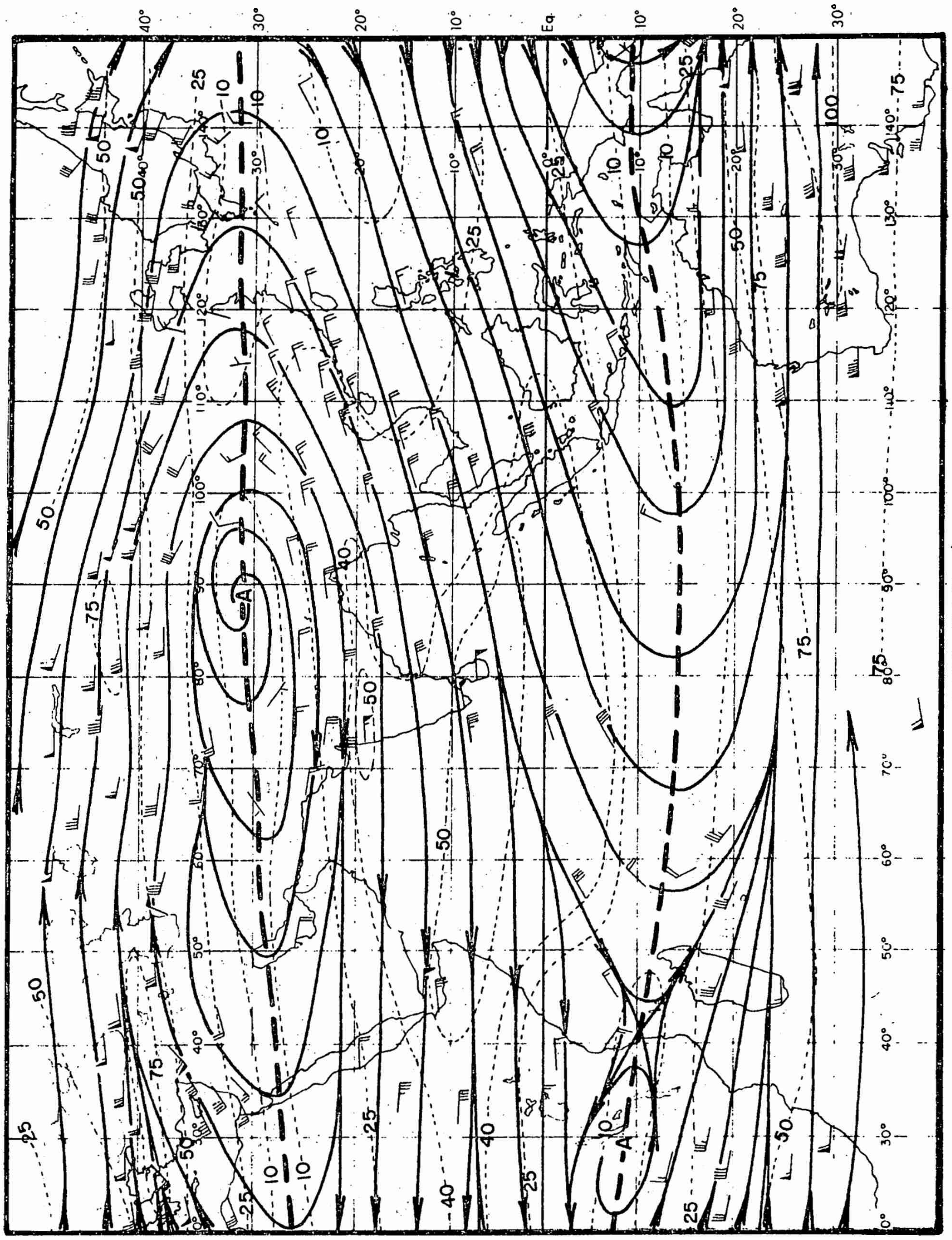


MAY, 200 mb

Figure 30

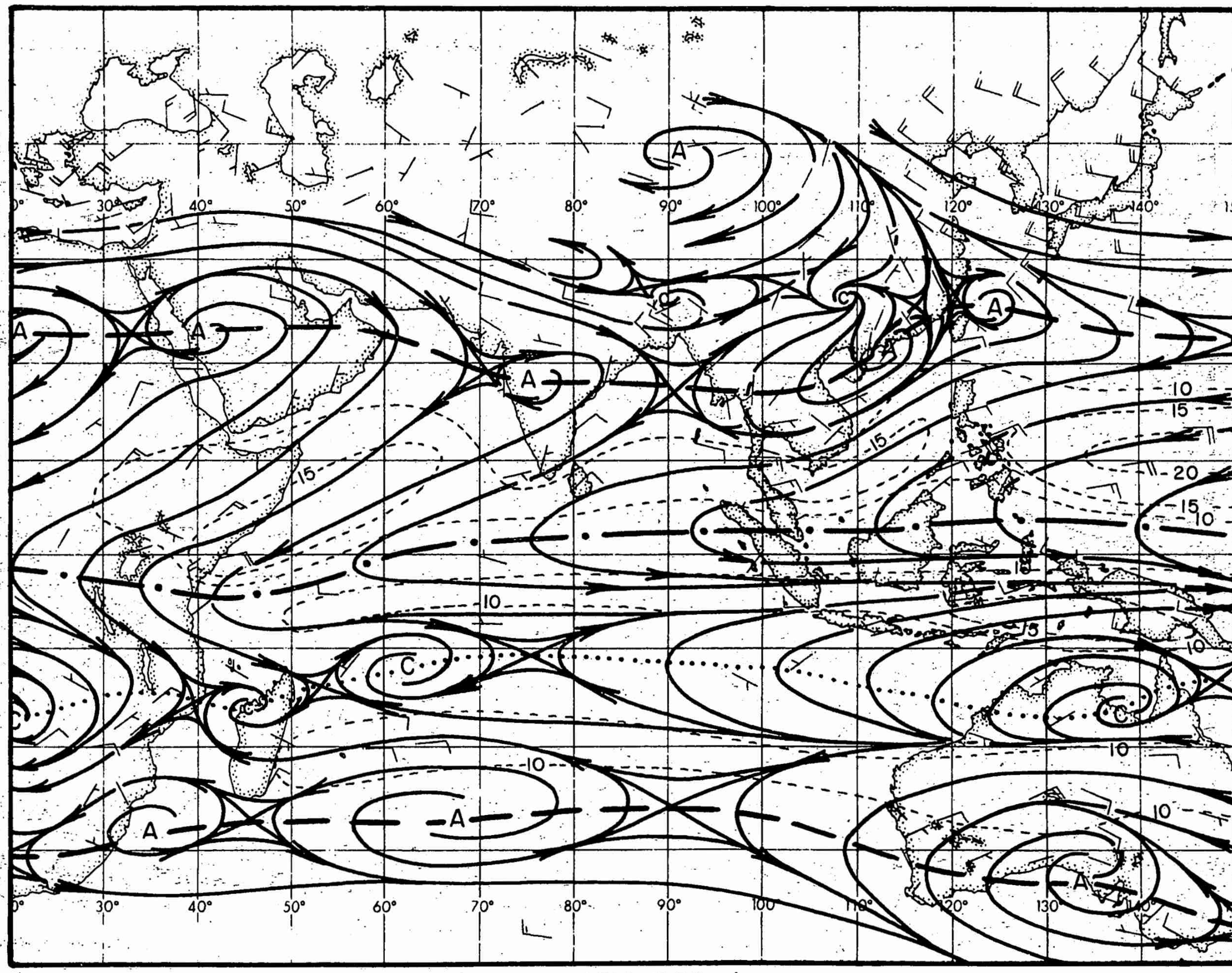


JULY, 850 mb
Figure 31



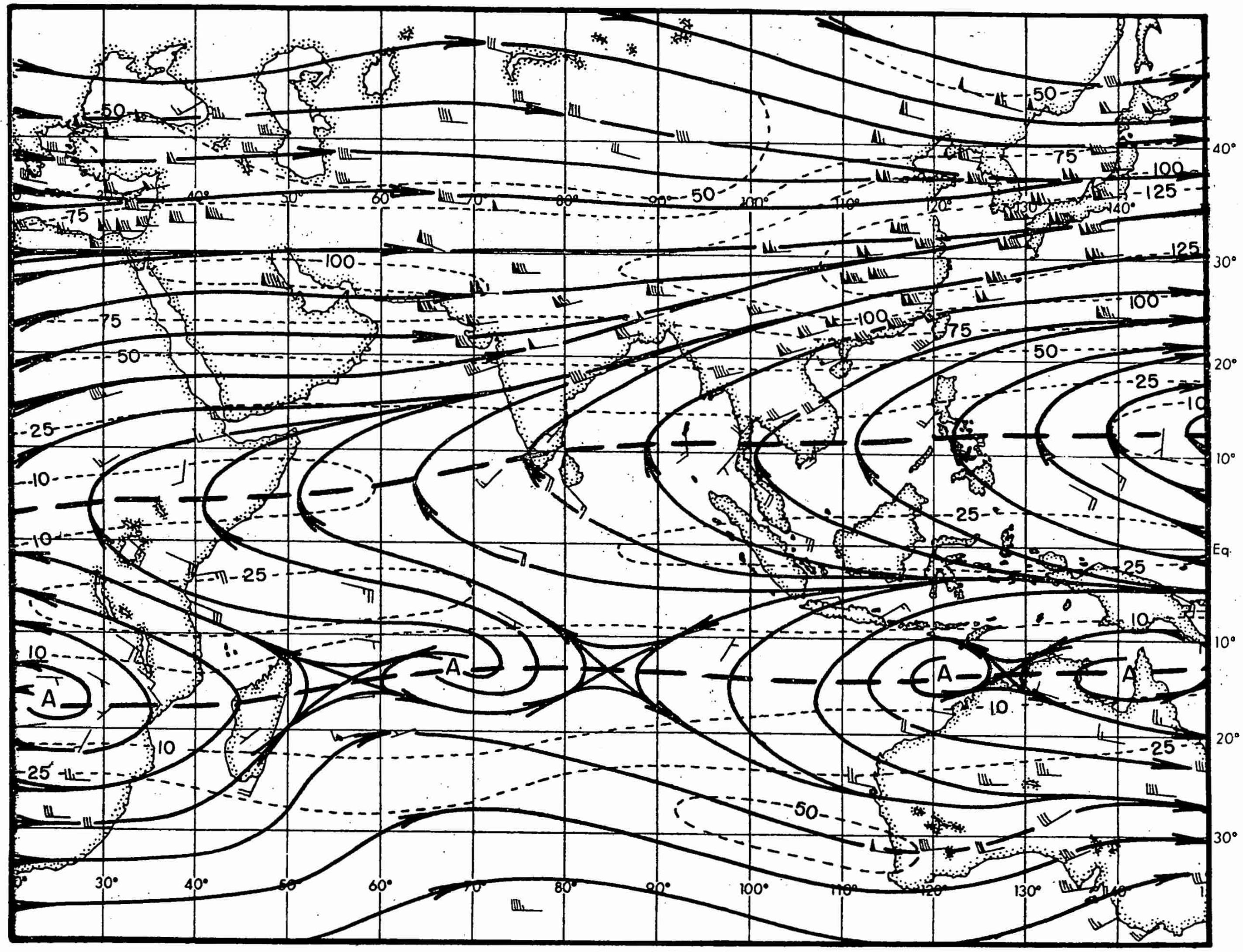
JULY, 200 mb

Figure 32



JANUARY, 850 mb

Figure 33



JANUARY, 200mb

Figure 34

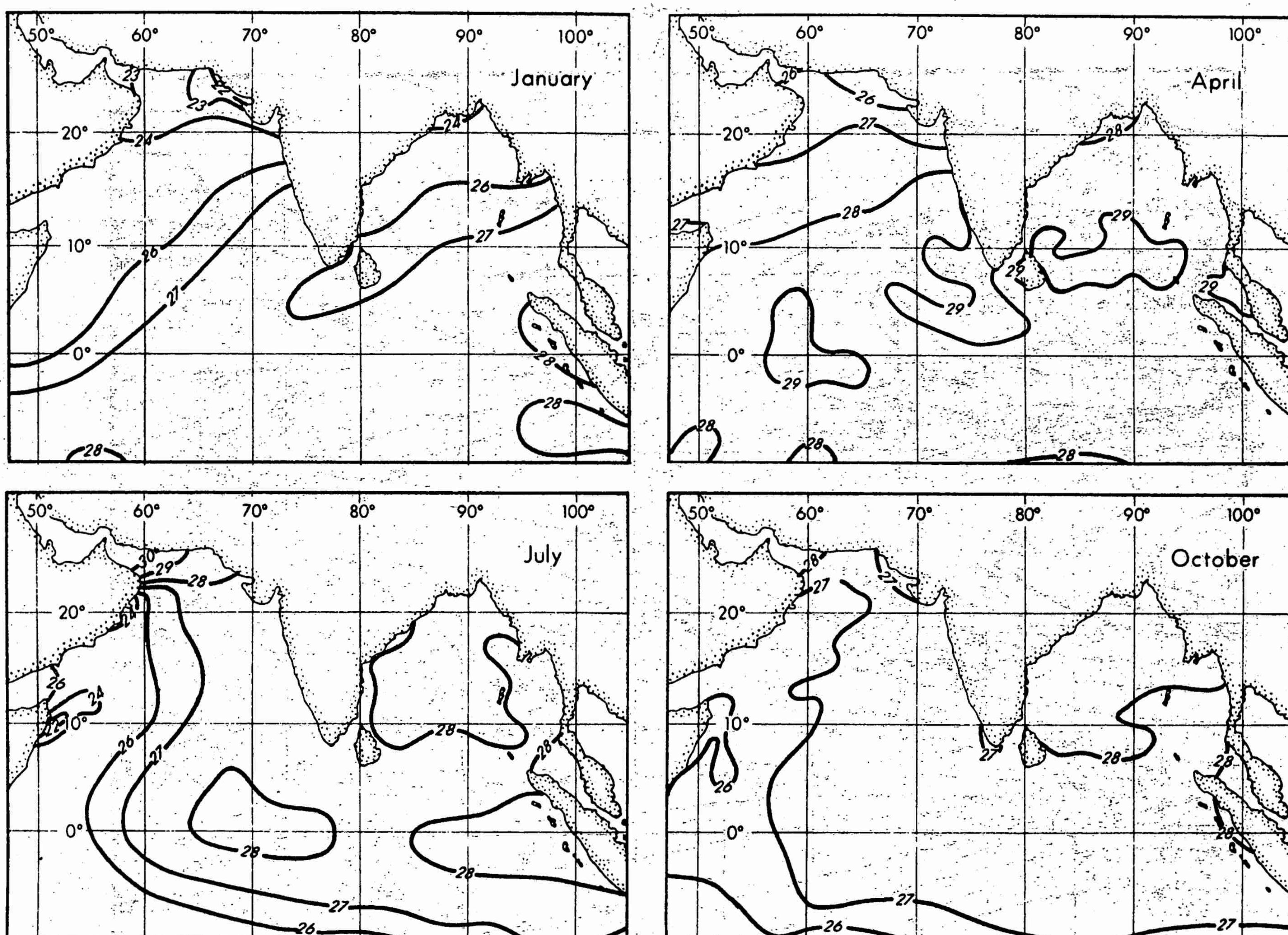
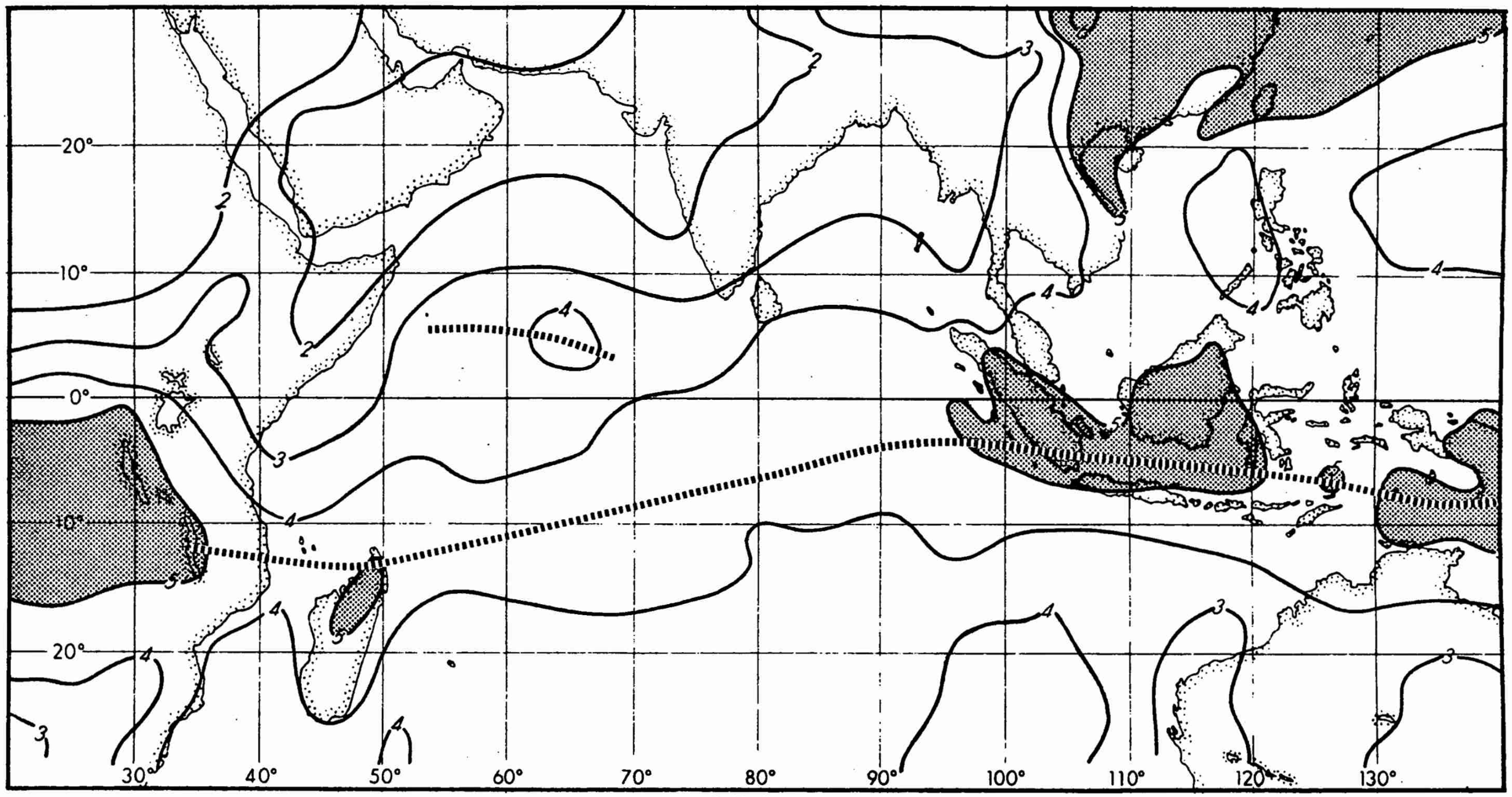


Figure 35. Mean sea-surface temperatures of the northern Indian Ocean for January, April, July, and October.



JAN

Figure 36. Mean cloudiness (in octas) over the Indian Ocean (January).

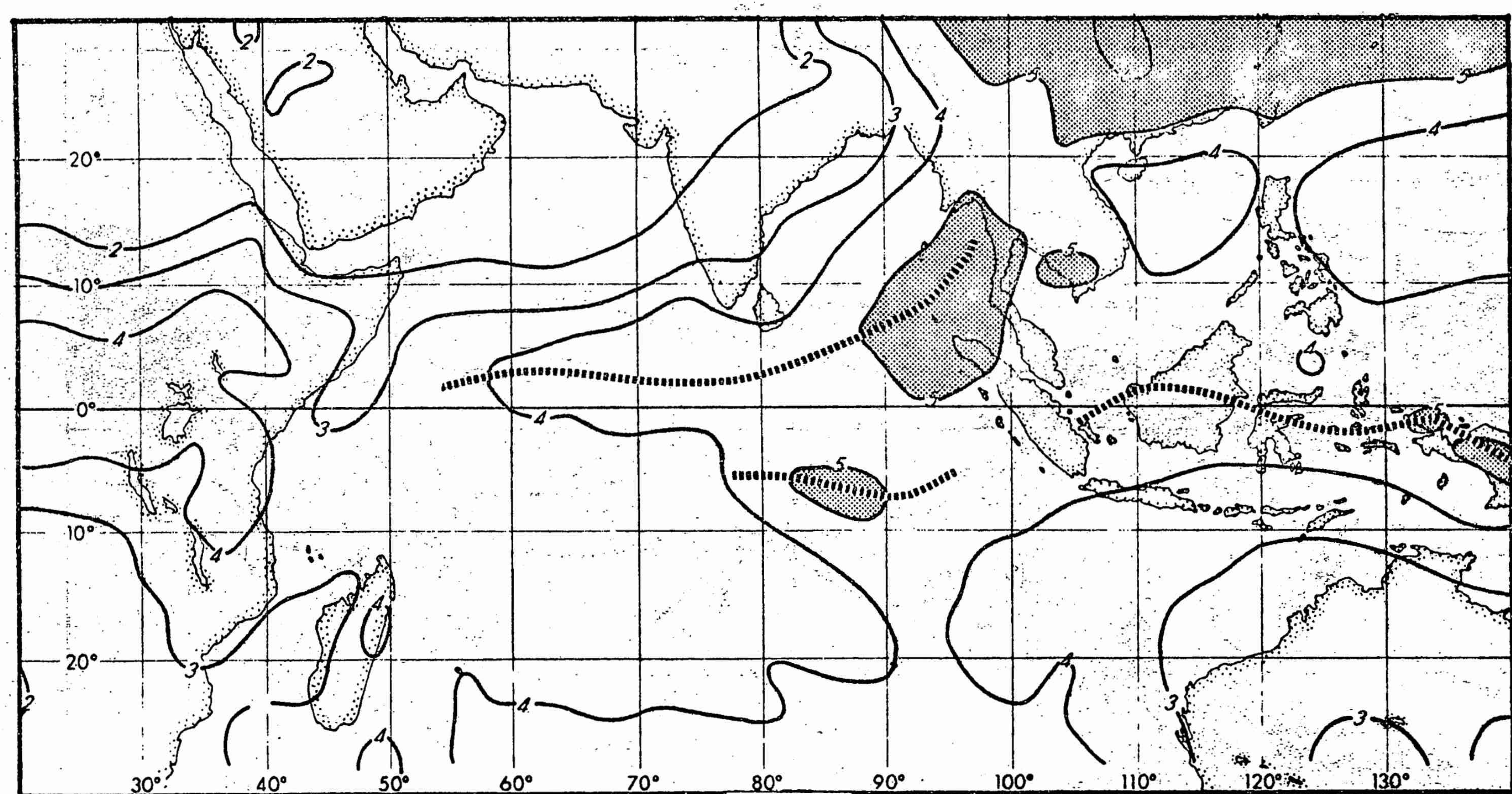


Figure 37. Mean cloudiness (in octas) over the Indian Ocean (May).

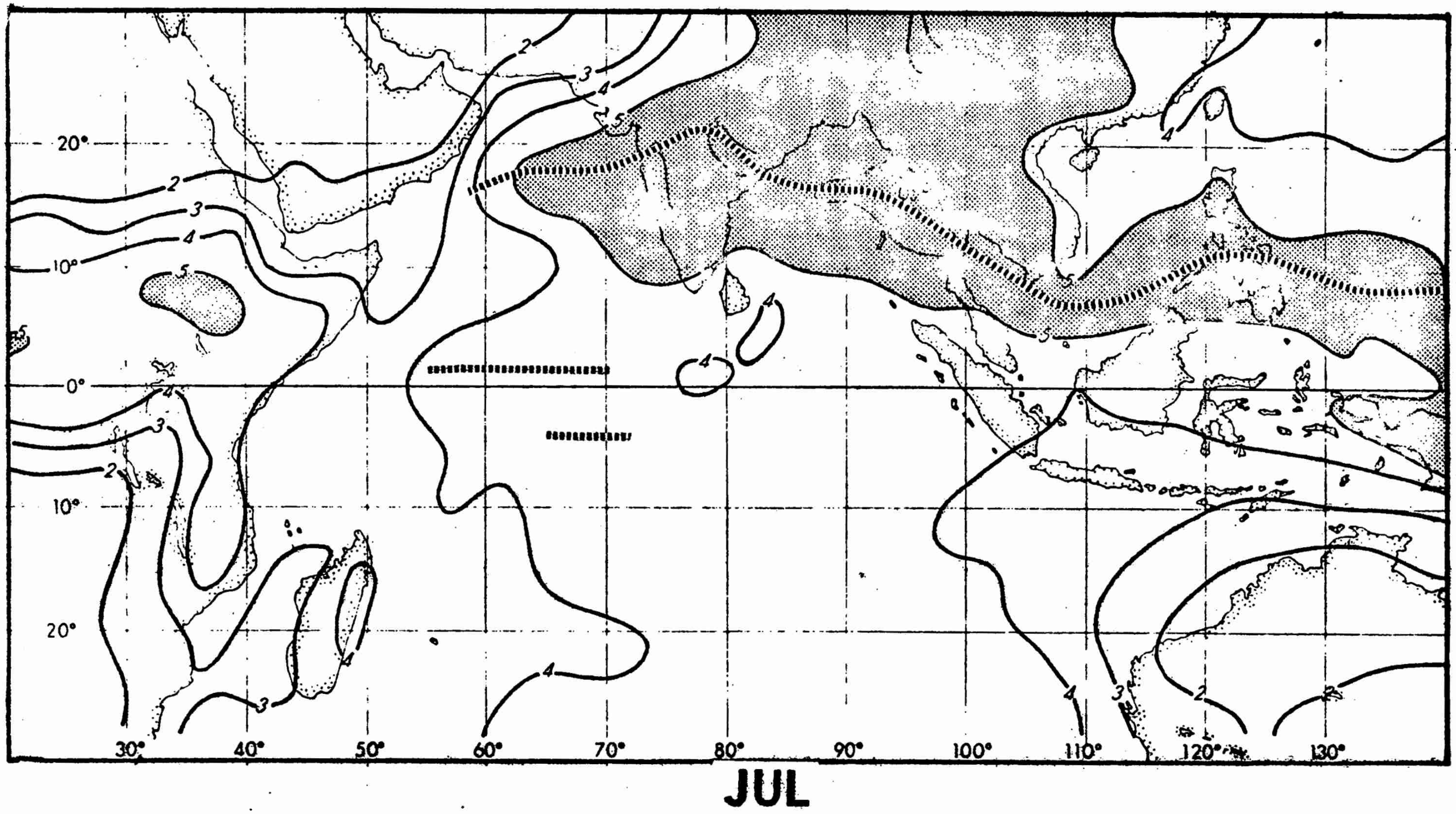
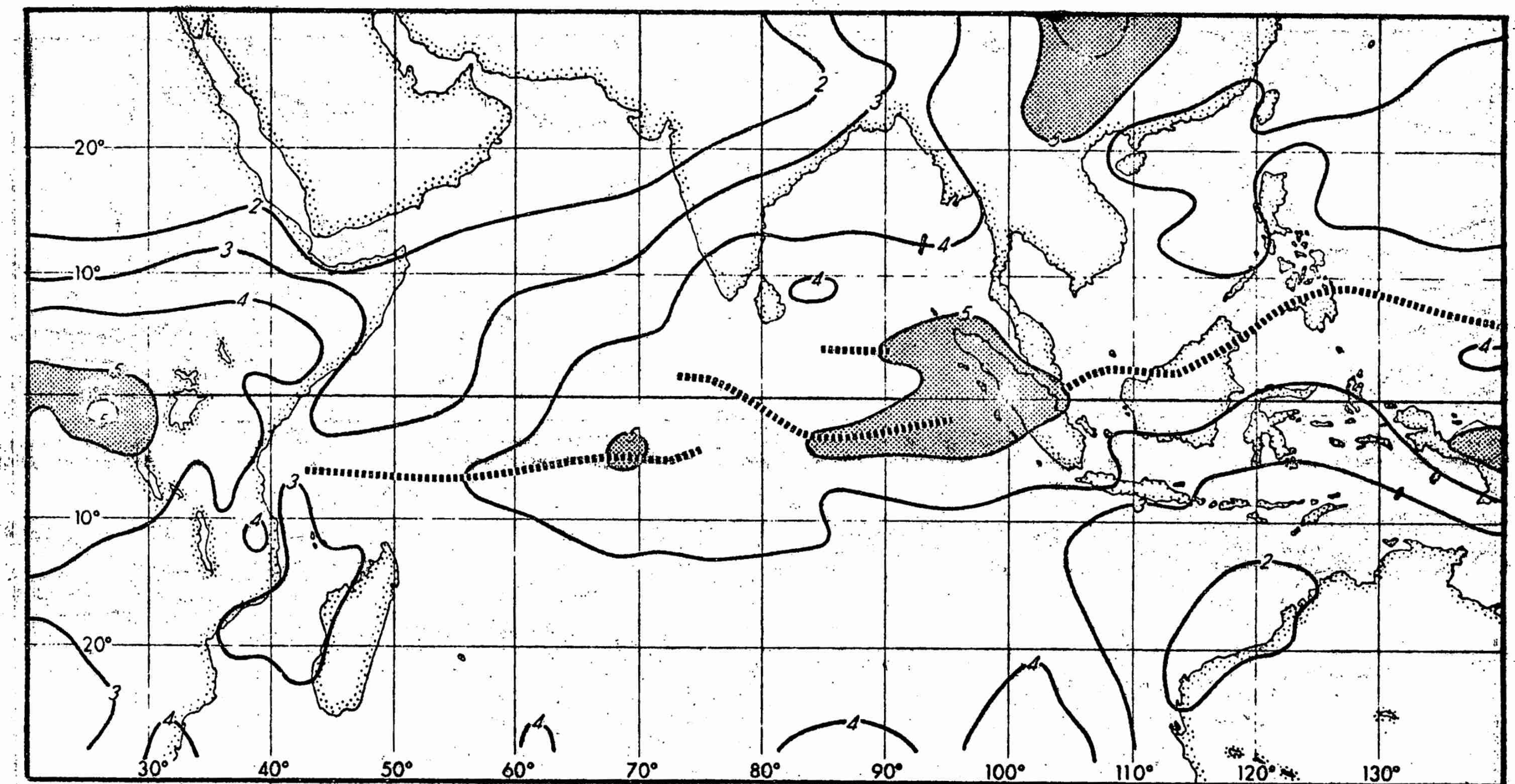


Figure 38. Mean cloudiness (in octas) over the Indian Ocean (July).



OCT

Figure 39. Mean cloudiness (in octas) over the Indian Ocean (October)

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Security Classification

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13. ABSTRACT

Photographs from polar-orbiting meteorological satellites were used in this study to obtain the frequency and tracks of depressions, storms, and hurricanes in the North Indian Ocean from November 1966 through December 1970 plus October 1971.

The distribution of the mean sea-surface temperature, cloudiness, and atmospheric circulation for selected months are discussed in relation to the observed cyclone climatology. Appropriate and pertinent climatic charts of these parameters are presented.

The results from the satellite period are compared with the 70-year (1891-1960) climatology of cyclonic storms from the India Meteorological Department (1964). Plotted cyclone tracks derived from satellite data are presented, as are plotted monthly tracks developed by the India Meteorological Department.

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